THE THUNDERSTORM AND ITS PHENOMENA.

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Introduction.—A thunderstorm, as its name implies, is a storm characterized by thunder and lightning, just as a dust storm is one characterized by a great quantity of flying dust. But the dust is never in any sense the cause of the storm that carries it along, nor, so far as known, does either thunder or lightning have any influence on the course—genesis, development, or termination—of even those storms of which they form, in some respects, the most important features. No matter how impressive nor how terrifying these phenomena may be, they never are anything more than mere incidents to or products of the peculiar storms they accompany, as will be made clear by what follows. In short, they are never in any sense either storm-originating or storm-controlling factors.

Origin of thunderstorm electricity.—A knowledge, or at least a good working hypothesis, of how the great amount of electricity incident to thunderstorms is generated, is absolutely essential to their logical explanation; that is, to a clear understanding of the probable interrelations between their many phenomena. Fortunately such an hypothesis, or theory, rather, since it is abundantly supported by observations and by laboratory experiments, is available as a result of work done on this subject in India by Dr. G. C. Simpson (1) of the Indian Meteorological Department.

Dr. Simpson's observations, just referred to, were obtained at Simla, India, at an elevation of about 7,000 feet above sea level, and covered all of the monsoon seasons, that is, roughly, April 15 to September 15, of 1908 and 1909. He also obtained observations of the electrical conditions of the snow at Simla during the winter of 1908–9.

A tipping-bucket rain gage gave an automatic continuous record of the rate and time of rainfall, while a Benndorf (2) self-registering electrometer marked the sign and potential of the charge acquired during each two-minute interval. A second Benndorf electrometer registered the potential gradient near the earth, and a coherer of the type used in radiotelegraphy registered the occurrence of each lightning discharge.

All obvious sources of error were examined and carefully guarded against. Hence it would seem that the conclusions drawn from the thousands of observations given in the memoir are fully justified; and especially so since several independent series of similar observations made at different times, by different people, and at places widely separated, have given confirmatory results in every case. Simpson's records show that—

(1) The electricity brought down by the rain was sometimes positive and sometimes negative.

(2) The total quantity of positive electricity brought down by the rain was 3.2 times greater than the total quantity of negative electricity.

(3) The period during which positively charged rain fell was 2.5 times longer than the period during which negatively charged rain fell.

(4) Treating charged rain as equivalent to a vertical current of electricity, the current densities were generally smaller than 4×10^{-15} amperes per square centimeter; but on a few occasions greater current densities, both positive and negative, were recorded.

(5) Negative currents occurred less frequently than positive currents, and the greater the current density the greater the preponderance of the positive currents.

(6) The charge carried by the rain was generally less than 6 electrostatic units per cubic centimeter of water, but larger charges were occasionally recorded, and in one exceptional storm (May 13, 1908) the negative charge exceeded 19 electrostatic units per cubic centimeter.

(7) As stated in paragraph (3) above, positive electricity was recorded more frequently than negative, but the excess was the less marked the higher the charge on the rain.

(8) With all rates of rainfall positively charged rain occurred more frequently than negatively charged rain, and the relative frequency of positively charged rain increased rapidly with increased rate of rainfall. With rainfall of less than about 1 millimeter in two minutes, positively charged rain occurred twice as often as negatively charged rain, while with greater intensities it occurred 14 times as often.

(9) When the rain was falling at a less rate than about 0.6 millimeter in two minutes, the charge per cubic centimeter of water decreased as the intensity of the rain increased.

(10) With rainfall of greater intensity than about 0.6 millimeter in two minutes the positive charge carried per cubic centimeter of water was independent of the rate of rainfall, while the negative charge carried decreased as the rate of rainfall increased.

(11) During periods of rainfall the potential gradient was more often negative than positive, but there were no clear indications of a relationship between the sign of the charge on the rain and the sign of the potential gradient.

(12) The data do not suggest that the negative electricity occurs more frequently during any particular period of a storm than during any other.

Concerning his observation on the electrification of snow Dr. Simpson says:

As far as can be judged from the few measurements made during the winter of 1908–9 it would appear that:

(1) More positive than negative electricity is brought down by snow in the proportion of about 3.6 to 1.

(2) Positively charged snow falls more often than negatively charged.

(3) The vertical electric currents during snowstorms are on the average larger than during rainfall.

(4) The charge per unit mass of precipitation is larger during snowfall than during rainfall.

While these observations were being secured a number of well-devised experiments were made to determine the electrical effects of each obvious process that takes place in the thunderstorm.

Freezing and thawing, air friction, and other things were tried, but none produced any electrification. Finally, on allowing drops of *distilled* water to fall through a vertical blast of air of sufficient strength to produce some spray, positive and important results were found, showing:

(1) That breaking of drops of water is accompanied by the production of both positive and negative ions.

(2) That three times as many negative ions as positive ions are released.

Now, a strong upward current of air is one of the most conspicuous features of the thunderstorm. It is always evident in the turbulent cauliflower heads of the cumulus cloud, the parent, presumably, of all thunderstorms. Besides, its inference is compelled by the occurrence of hail, a frequent thunderstorm phenomenon, whose formation requires the carrying of raindrops and the growing hailstones repeatedly to cold and therefore high altitudes. And from the existence of hail it is further inferred that an updraft of at least 8 meters per second must often occur within the body of the storm, since, as experiment shows, it requires approximately this velocity to support the larger drops, and even a greater velocity to support the average hailstone.

Experiment also shows that rain can not fall through air of ordinary density whose upward velocity is greater than about 8 meters per second, or itself fall with greater velocity through still air; that in such a current, or with such a velocity, drops large enough, if kept intact, to force their way down, or, through the action of gravity, to attain a greater velocity than 8 meters per second with reference to the air, whether still or in motion, are so blown to pieces that the increased ratio of supporting area to total mass causes the resulting spray to be carried aloft or left behind, together with, of course, all original smaller drops. Clearly, then, the updrafts within a cumulus cloud frequently must break up at about the same level innumerable drops which, through coalescence, have grown beyond the critical size, and thereby, according to Simpson's experiments, produce electrical separation within the cloud itself. Obviously, under the turmoil of a thunderstorm, its choppy surges and pulses, such drops may be forced through the cycle of union (facilitated by any charges they may carry) and division, of coalescence and disruption, from one to many times, with the formation on each at every disruption, again *according to experiment* of a correspondingly increased electrical charge. The turmoil compels mechanical contact between the drops, whereupon the charges break down the surface tension and insure coalescence. Hence, once started, the electricity of a thunderstorm rapidly grows to a considerable maximum.

After a time the larger drops reach, here and there, places below which the updraft is small—the air can not be rushing up everywhere—and then fall as positively charged rain, because of the processes just explained. The negative electrons in the meantime are carried up into the higher portions of the cumulus, where they unite with the cloud particles and thereby facilitate their coalescence into negatively charged drops. Hence, the heavy rain of a thunderstorm should be positively charged, as it almost always is, and the gentler portions negatively charged which very frequently is the case.

Such in brief is Dr. Simpson's theory of the origin of the electricity in thunderstorms, a theory that fully accounts for the facts of observation and in turn is itself abundantly supported by laboratory tests and simulative experiments.

If this theory is correct, and it seems well founded, it must follow that the one essential to the formation of the giant cumulus cloud, namely, the rapid uprush of moist air, is also the one essential to the generation of the electricity of thunderstorms. Hence the reason why lightning seldom if ever occurs except in connection with a cumulus cloud is understandable and obvious. It is simply because the only process that can produce the one is also the process that is necessary and sufficient for the production of the other.

The violent motions of cumulus clouds.—From observations, and from the graphic descriptions of the few balloonists who have experienced the trying ordeal of passing through the heart of a thunderstorm, it is known that there is violent vertical motion and much turbulence in the middle of a large cumulus cloud, a fact which so far as it relates to the theory alone of the thunderstorm, it would be sufficient to accept without inquiring into its cause. However, to render the discussion more nearly complete, it perhaps is worth while, since it is a mooted question, to inquire what the probable cause of the violent motions in large cumulus clouds really is—motions which, in the magnitude of their vertical components and degree of turmoil, are never exhibited by clouds of any other kind nor met with elsewhere by either manned, sounding, or pilot balloons.

It has been shown by von Bezold (3) that sudden condensation from a state of supersaturation, and also sudden congelation of undercooled cloud droplets, would, as a result of the heat thus liberated, cause an equally sudden expansion of the atmosphere, and thereby turbulent motions analogous to those observed in large cumuli. However, as von Bezold himself points out, it is not evident how either the condensation or the freezing could suddenly take place throughout a cloud volume great enough to produce the observed effects. Besides, these eruptive turmoils, whatever their genesis, undoubtedly originate and run their course in regions already filled with cloud particles in the presence of which no appreciable degree of supersaturation can occur. Hence the rapid uprush and the violent turbulence in question obviously must have some other cause; and this we shall find in the difference between the actual temperature gradient of the surrounding atmosphere and the adiabatic temperature gradient of the saturated air within the cloud itself.

Consider a warm summer afternoon, temperature 30° C., say, and assume the dew point to be 15° C. Now, the adiabatic decrease of temperature of nonsaturated air is about 1° C. per 100 meters change in elevation, and therefore, under the assumed conditions, vertical convection of the surface air causes condensation to begin at an elevation of approximately 1.5 kilometers. From this level, however, so long as the cloud particles are carried up with the rising air, the rate of temperature decrease, for at least a couple of kilometers, is much less—at first about one-half the previous rate. After a considerable rise above the level of initial condensation, half a kilometer, say, the raindrops have so increased in size as to lag behind the upward current and even to drop out, while, at the same time, the amount of moisture condensed per degree fall of temperature grows rapidly less. Hence, for both reasons—because the heat of the condensed water is no longer available to the air from which it was condensed, the drops having been left behind, and because but little latent heat is to be had from further condensation, there being but little water vapor left—the rate of temperature decrease again approaches the adiabatic gradient of dry air, or 1° C. per 100 meters change of elevation.

Obviously, then, for some distance above the level at which condensation begins to set free its latent heat, the temperature of the rising mass of moist air departs farther and farther from the temperature of the surrounding atmosphere at the same level, and therefore its buoyancy for a time as steadily increases. But, of course, as explained above, this increase of buoyancy does not continue to any great altitude.

In the lower atmosphere continuous and progressive convection builds up the adiabatic gradient so gradually that no great difference between the temperature of the rising column and that of the adjacent atmosphere is anywhere possible. Hence, under ordinary conditions, the uprush in this region is never violent. But whenever the vertical movement of the air brings about a considerable condensation it follows, as above explained, that there is likely to be an increase in its buoyancy, and hence a more or less rapid upward movement of the central portion, like air up a heated chimney, and for the same reason, together with, because of viscosity, a rolling and turbulent motion of the sides, of the type so often seen in towering cumulus clouds. Obviously, too, the uprushing column of air must ascend somewhat beyond its point of equilibrium, and then, because slightly undercooled, correspondingly drop back.

Figure 1, based upon approximately average conditions, illustrates the points just explained. The elevation is in kilometers and the temperature in degrees centigrade.

AB is the approximate temperature gradient for nonsaturated air, about 1° C. per 100 meters change in elevation. *GCKDEF* is the supposed temperature gradient before convection begins, or a decrease, in accordance with observations, of 6° C., approximately, per kilometer increase of elevation, except near the surface, where the temperature decrease, before convection has begun, ordinarily is less rapid.

As convection sets in, the temperature decrease near the surface soon approximates the adiabatic gradient for dry air, and this condition extends gradually to greater altitudes, till, in the assumed case, condensation begins at the level *C*, or where the temperature is 15° C. Here the temperature decrease, under the assumed conditions, suddenly changes from 10° C. per kilometer increase of elevation to rather less than half that amount, but slowly increases with increase of altitude and consequent decrease of temperature. At some level, as *L*, the temperature difference between the rising and the adjacent air is a maximum. At *D* the temperature of the rising air is the same as that of the air adjacent, but its momentum presumably carries it on to some such level as *H*. Within the rising column, then, the temperature gradient is

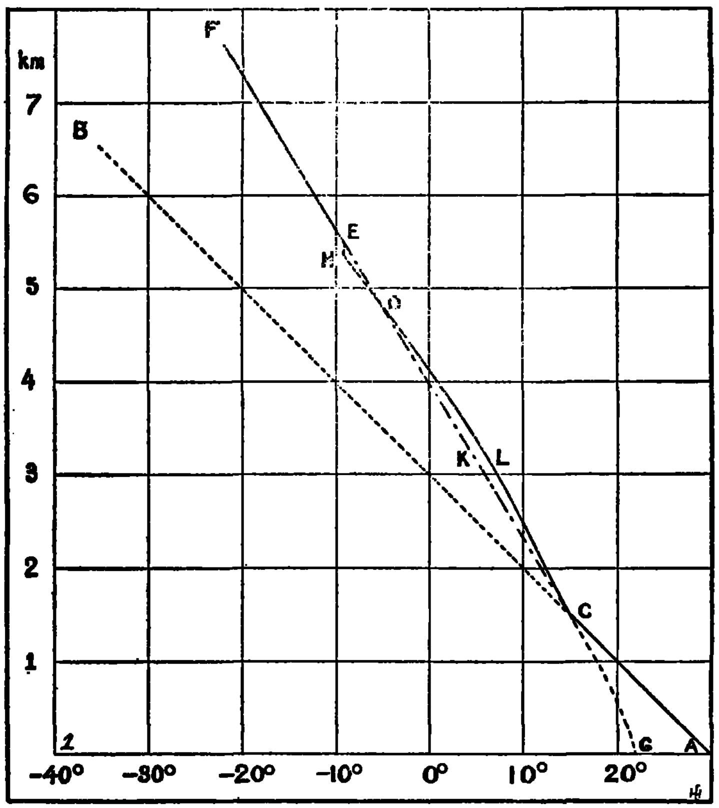

FIG. 1.—Temperature gradients within (CLD) and without (CKD) cumulus clouds.

approximately given by the curve *ACLDHE*, while the temperature gradient of the surrounding air is given by the curve *ACKDEF*.

The cause, therefore, of the violent uprush and turbulent condition within large cumulus clouds is, presumably, the difference between the temperature of the inner or warmer portions of the cloud itself and that of the surrounding atmosphere at the same level, as indicated by their respective temperature gradients *CLD* and *CKD*. Clearly, too, while some air must flow into the condensation column all along its length, the greatest pressure difference, and, therefore, the greatest inflow, obviously is at its base. After the rain has set in, however, this basal inflow is from immediately in front of the storm, and necessarily so, as will be explained later.

Convectional instability.—Rapid vertical convection of humid air, as we have seen, is essential to the production of the cumulus cloud and, therefore, to the generation of the thunderstorm. Hence it is essential to consider the conditions under which the vertical temperature gradient necessary to this convection can be established. These are:

1. Strong surface heating, especially in regions of light winds; a frequent occurrence.

The condition that the winds be light is not essential, or, perhaps, even favorable to the genesis of all thunderstorms—only the local or heat variety, and favorable to these simply because heavy winds tend to prevent the formation of isolated rising columns of air, the progenitors of this particular type of storm.

2. The overrunning of one layer of air by another at a temperature sufficiently lower to induce convection, wellnigh the sole cause of ocean thunderstorms and also of frequent occurrence on land.

3. The underrunning and consequent uplift of a saturated layer of air by a denser layer; a frequent occurrence to a greater or less extent and, presumably, therefore at least an occasional one of sufficient magnitude to produce a thunderstorm.

Here the underrunning air lifts both the saturated layer and the superincumbent unsaturated layer, and thereby forces each to cool adiabatically. But as both layers are lifted equally while, because of the latent heat of condensation, the saturated layer cools much slower than the dry, it follows that a sufficient mechanical lift of a saturated layer of air would establish between it and the nonsaturated layer above a superadiabatic temperature gradient and thereby produce local convection, cumulus clouds, and, perhaps, a thunderstorm.

Periodic recurrence of thunderstorms.—While thunderstorms may occur at any hour of any day they nevertheless have three distinct periods of maximum occurrence: *a*, daily, *b*, yearly, and *c*, irregularly cyclic. Each maximum depends upon the simple facts that the more humid the air and the more rapid the local vertical convections the more frequent and also the more intense the thunderstorms, for the obvious reason that it is rapid vertical convection of humid air that produces them.

Daily land period.—Vertical convection of the atmosphere over land areas is most pronounced when the surface is most heated; that is, during afternoons. Hence the hours of maximum frequency of inland or continental thunderstorms are, in most places, 2 to 4 p. m.

Daily ocean period.—Because of evaporation and of the high specific heat of water the surface temperature of the ocean increases but little during the day, and because of convection it decreases but slightly at night. Indeed, the diurnal temperature range of the ocean surface usually is but a small fraction of one degree C., while that of the atmosphere at from 500 to 1,000 meters elevation is several fold as great (4). Hence those temperature gradients over the ocean that are favorable to rapid vertical convection are most frequent during the early morning hours, and, therefore, the maximum of ocean thunderstorms usually occurs between midnight and 4 a. m.

Yearly land period.—Just as inland thunderstorms are most frequent during the hottest hours of the day, so too, and for the same reason, they are, in general, most frequent over the land during the hottest months of the year, or, rather, during those months when the amount of surface heating and, therefore, the vertical temperature gradient is a maximum.

Hence, in middle latitudes, where there are no late spring snows to hold back the temperatures, the month of maximum frequency often is June. In higher latitudes, where the strong surface heating is more or less delayed, the maximum occurs in July or even August.

Yearly ocean period.—Over the oceans, on the other hand, temperature gradients favorable to the genesis of thunderstorms, and, therefore, the storms themselves, occur most frequently during the winter and least frequently during the summer. This is because the temperature of the air at some distance above the surface, being largely what it was when it left the windward continent, greatly changes from season to season while that of the water, and, of course, the air in contact with it, changes but little through the year. That is, over the oceans the average decrease of temperature with increase of elevation obviously is least and, therefore, thunderstorms fewest in summer, and greatest, with such storms most numerous, in winter.

Cyclic land period.—Since thunderstorms are accompanied by rain and since over land they are most numerous during summer, it would appear that they must occur most frequently either in warm or in wet years and least frequently in cold or in dry years. Further, if it should happen, as it actually does, that, for the earth as a whole, warm years are also wet years and dry years cold years, it would appear logically certain that, for the entire world, the maximum number of thunderstorms must belong to the years that are wet and warm and the minimum to those that are cold and dry.

A complete statistical examination of these statements is not possible, owing to the fact that meteorological data are available for only portions of the earth's surface and not for the whole of it. Nevertheless, well-nigh conclusive data do exist. The annual rainfall, for instance, to the leeward of a large body of water obviously must bear the same relation to the annual average windward temperature that the total annual precipitation over the entire world does to the annual average world temperature. In each case the amount of evaporation or amount of water vapor taken into the atmosphere, and, therefore, the amount of subsequent precipitation, clearly must increase and decrease with the temperature. An excellent test and complete support of this deduction is furnished by figure 2, in which the full line represents the smoothed annual European precipitation (5), and the dotted line smoothed annual average eastern American temperatures.

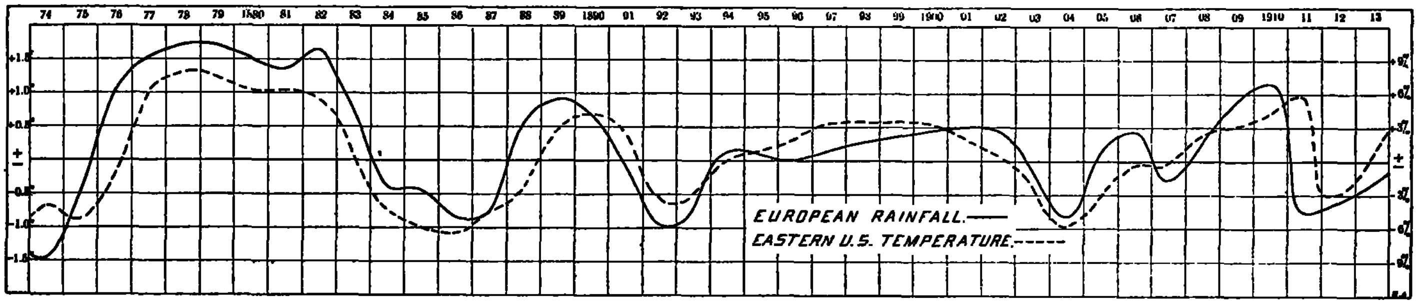

FIG. 2.—Relation of European rainfall to eastern U. S. temperature.

Beyond a reasonable doubt, therefore, for the world as a whole, warm years are wet and cold ones are dry. Hence, as above stated, it is practically certain that the maxima of thunderstorms occur during years that are wet, or warm, if we prefer, for the two are synchronous, and the minima during years that are dry, or cold. A partial and, so far as it goes, a confirmatory statistical test of this conclusion is given by figure 3. The lower group of curves is based on an exhaustive study by Dr. von Gulik (6) of thunderstorms and lightning injuries in Holland. The continuous zigzag line gives the actual annual number of thunderstorm days and the continuous curved line the same numbers smoothed. The broken lines give, respectively, the actual and the smoothed values of the annual average precipitation. The upper curve represents the variations in the smoothed number of destructive thunderstorms (7) (number of thunderstorm days not readily available) in Germany.

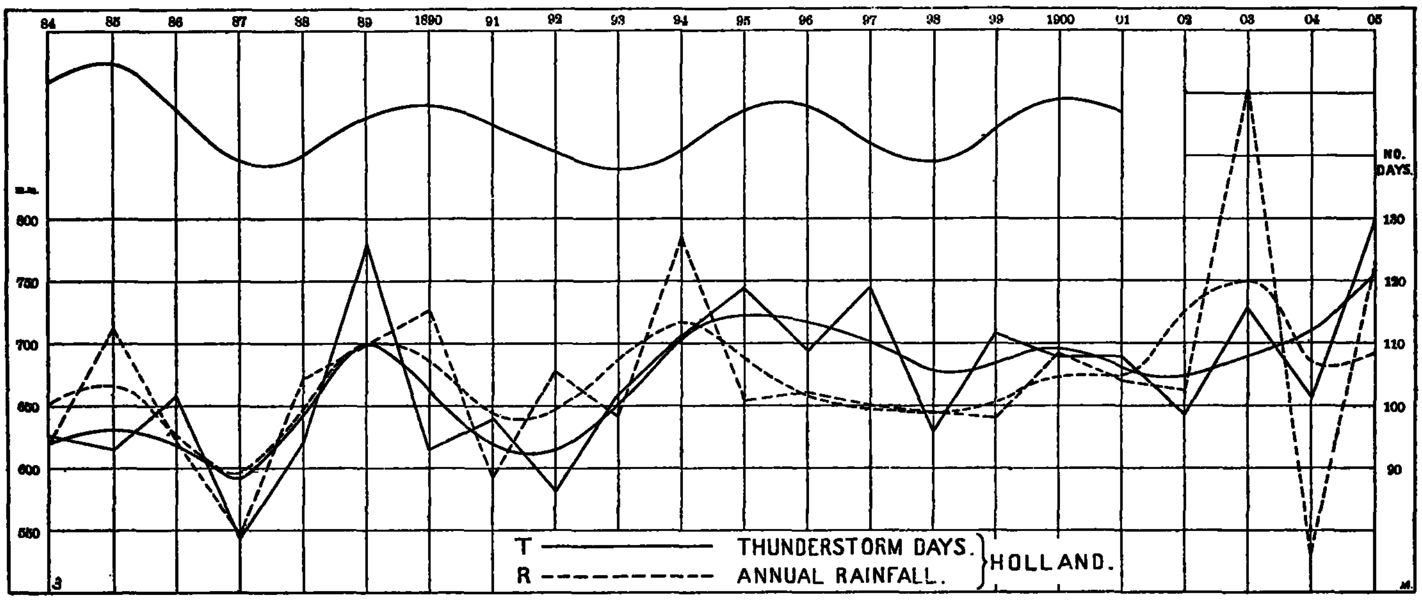

FIG. 3.—Relation of annual number of thunderstorm days to total annual precipitation—Holland. The uppermost, wavy curve shows the variation in the smoothed numbers of destructive thunderstorms in Germany.

The original data on which this last curve is based indicate a continuous and rapid increase of thunderstorm destructiveness. Presumably, however, this feature is real only to the extent that the country has become more densely populated and more thickly studded with destructible property. At any rate, this element has been omitted from the curve and only the variation factor retained.

It will be noted that the curve of thunderstorm frequency for all Holland closely parallels the curve of thunderstorm injury in all Germany. Hence, it seems safe to infer that the frequency of thunderstorms varies pretty much the same way over both countries, and, presumably, also over many other portions of Europe; that is, roughly as the rainfall varies, or, considering the world as a whole, roughly as the temperature varies.

Additional statistical evidence of the relation between the annual number of thunderstorms and the total annual precipitation, kindly assembled by the Climatological Division of the United States Weather Bureau, P. C. Day in charge, is shown by figure 4, in which the upper line gives, in millimeters, the smoothed average annual precipitations of 127 stations widely scattered over the whole of

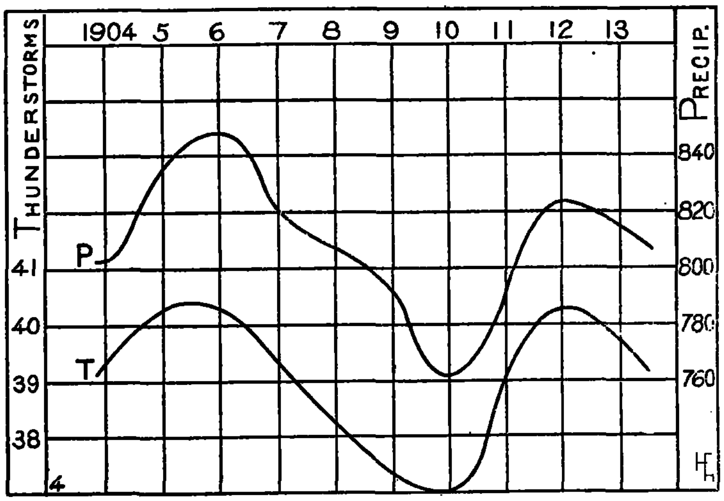

FIG. 4.—Relation of annual number of thunderstorms, T, to total annual precipitation, P, United States.

the United States, and the lower line the smoothed average annual number of thunderstorms at these same stations. It was thought at first that this relation might differ greatly for those portions of the United States whose climates are radically dissimilar, and for this reason the stations east of the one hundredth meridian provisionally were classed separately from those west of it; but the results for the two sections, being substantially alike, show that for this purpose their division is entirely unnecessary.

As will be seen from the figure the statistics of only the past 10 years have been used. This is because the annual number of such storms reported rapidly decreases from 1904 back to about 1890. Indeed, the annual number of thunderstorms reported per station during the past 10 years is almost double the annual number per station (practically the same stations) from 1880 to 1890. The transition from the smaller to the larger number was due in great measure, doubtless, to an alteration in station regulations that changed the official definition of a thunderstorm from "thunder *with* rain" to "thunder *with* or *without* rain." This, however, does not account for the fact that from 1890 to 1904 the average annual number of thunderstorms reported per station increased, at a nearly constant rate, almost 100 per cent. Either the storms did so increase, which seems improbable, or else there was, on the average, an increase of attention given to this particular phenomenon. At any rate, so continuous and so great an increase in the average number of thunderstorms can hardly be accepted without abundant confirmation, and for this reason the earlier thunderstorm records provisionally have been rejected.

Obviously a much closer relation between the number of thunderstorms and total precipitation would hold for some months and seasons than for others, but no such subgrouping of the data has been made, though, presumably, it would give interesting results. The whole purpose of this portion of the study was to arrive at some definite idea in regard to the cyclic change of thunderstorm frequency, to see with what other meteorological phenomena this change is associated, and, if possible, to determine its cause.

Now, it is well known that the average temperature of the world as a whole follows in general the sun-spot changes, in the sense that the greater the number of spots the lower the temperature and the smaller the number of spots the higher the temperature. This regular relation, however, often is greatly modified (8) by the presence in the high atmosphere of volcanic dust, one invariable effect of which is a lower average temperature. Hence, the warm and the cold periods are irregularly cyclic, and also irregular in intensity. Hence, also the annual amount of precipitation, the frequency of thunderstorms, and many other phenomena must perforce undergo exactly the same irregular cyclic variation.

As already stated the statistical evidence bearing on these conclusions neither is nor can be complete, but the deductions are so obvious and the statistical data already examined so confirmatory that but little doubt can exist of their general accuracy.

Cyclic ocean period.—The record of thunderstorms over the oceans is not sufficiently full to justify any conclusions in regard to their cyclic changes. Possibly, as in the yearly and the daily periods, the ocean cyclic period may be just the reverse of that of the land, but this is not certain.

Geographic distribution.—The geographic distribution of the thunderstorm may safely be inferred from the fact that it is caused by the strong vertical convection of humid air. From the nature of its formation one would assume, and the assumption is supported by observation, that the thunderstorm must be rare beyond either polar circle, especially over Greenland and over the Antarctic continent, rare over great desert regions wherever situated, and, on the other hand, increasingly abundant with increase of temperature and humidity, and, therefore, in general, most abundant in the more rainy portions of the equatorial regions. The east coast of South America from Pernambuco to Bahia is said to be an exception.

Pressure and temperature distribution.—In illustrating the occurrence of thunderstorms with reference to the disposition of isobars and isotherms, or the distribution of atmospheric pressure and temperature, typical weather maps of the United States,[1] figures 5–19, have been used, not because the thunderstorms of this country are different in any essential particular from those of other countries, but chiefly as a matter of convenience in making the drawings. To facilitate their study each of the several types discussed is illustrated with three consecutive maps. The first shows the 12-hour antecedent

[1] The author wishes to acknowledge the courteous cooperation of the Forecast Division, U. S. Weather Bureau, in selecting maps typical of thunderstorm conditions in the United States.

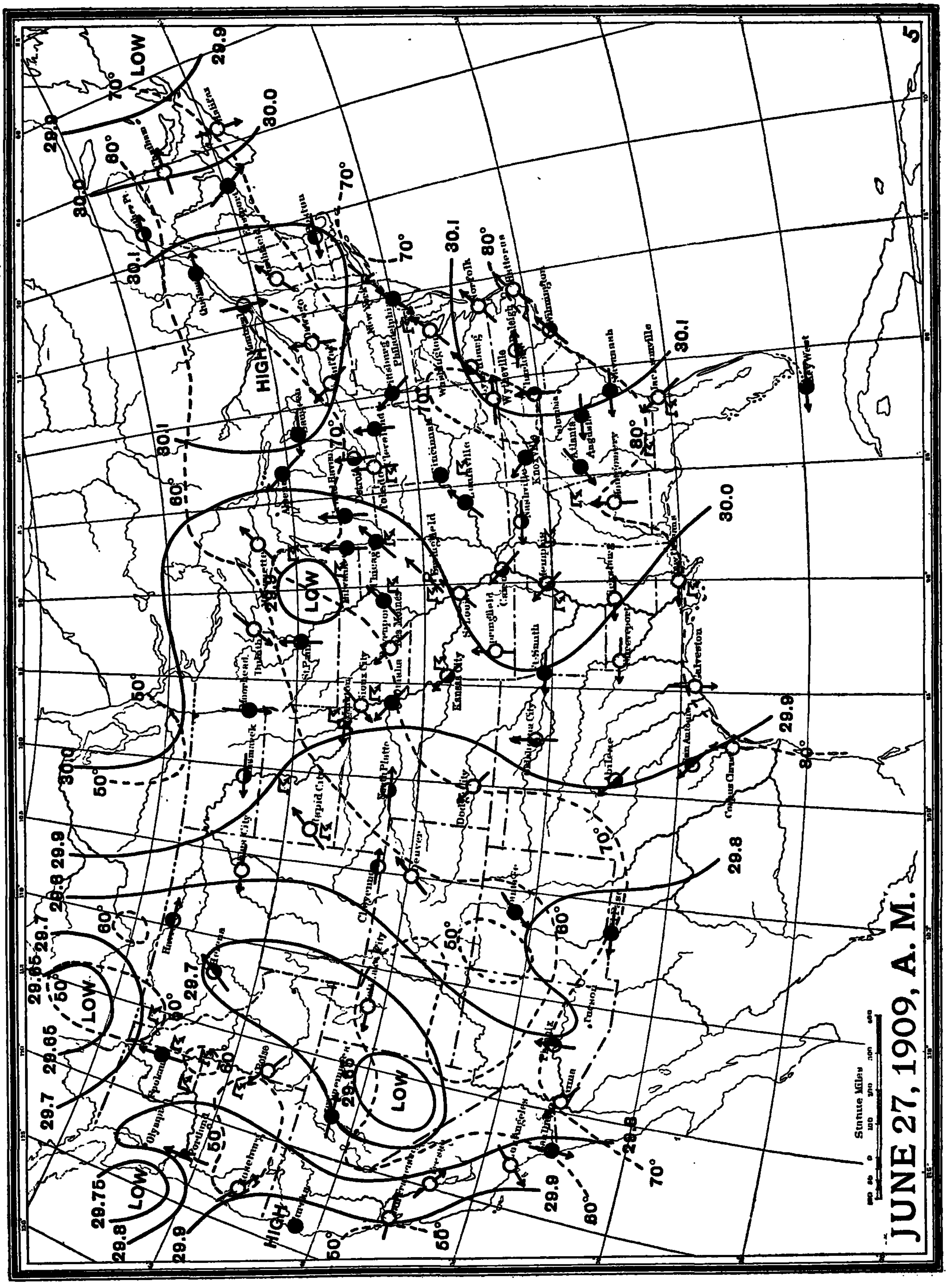

FIG. 5.—Weather Map, 8 a. m., June 27, 1909, typical of conditions at beginning of "heat" thunderstorms. ○ clear; ◐ partly cloudy; ● cloudy; R rain; ⊼ thunderstorm.

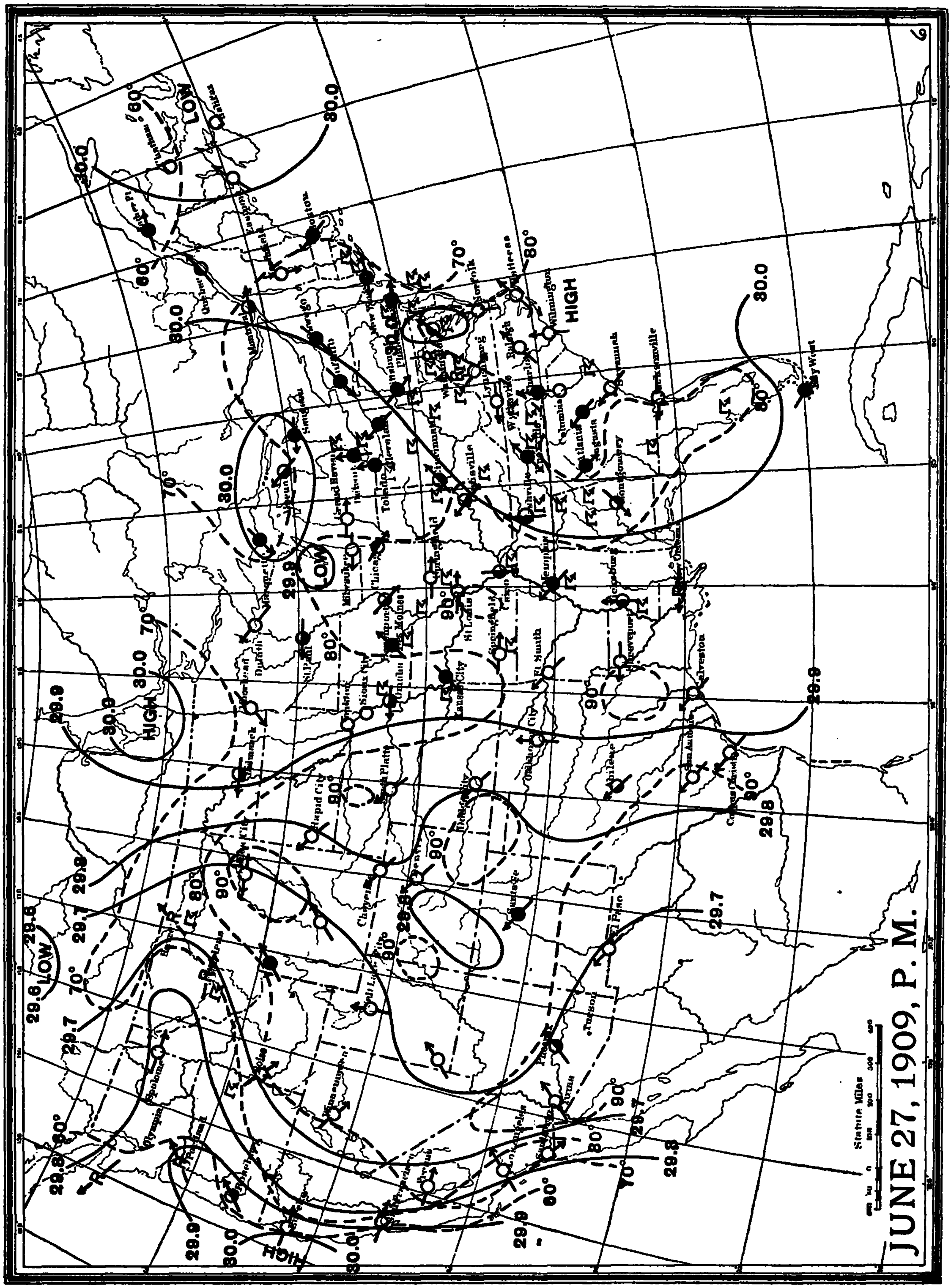

FIG. 6.—Weather Map, 8 p. m., June 27, 1909, typical of "heat" thunderstorms. ○ clear; ◐ partly cloudy; ● cloudy; R rain; ⊠ thunderstorms.

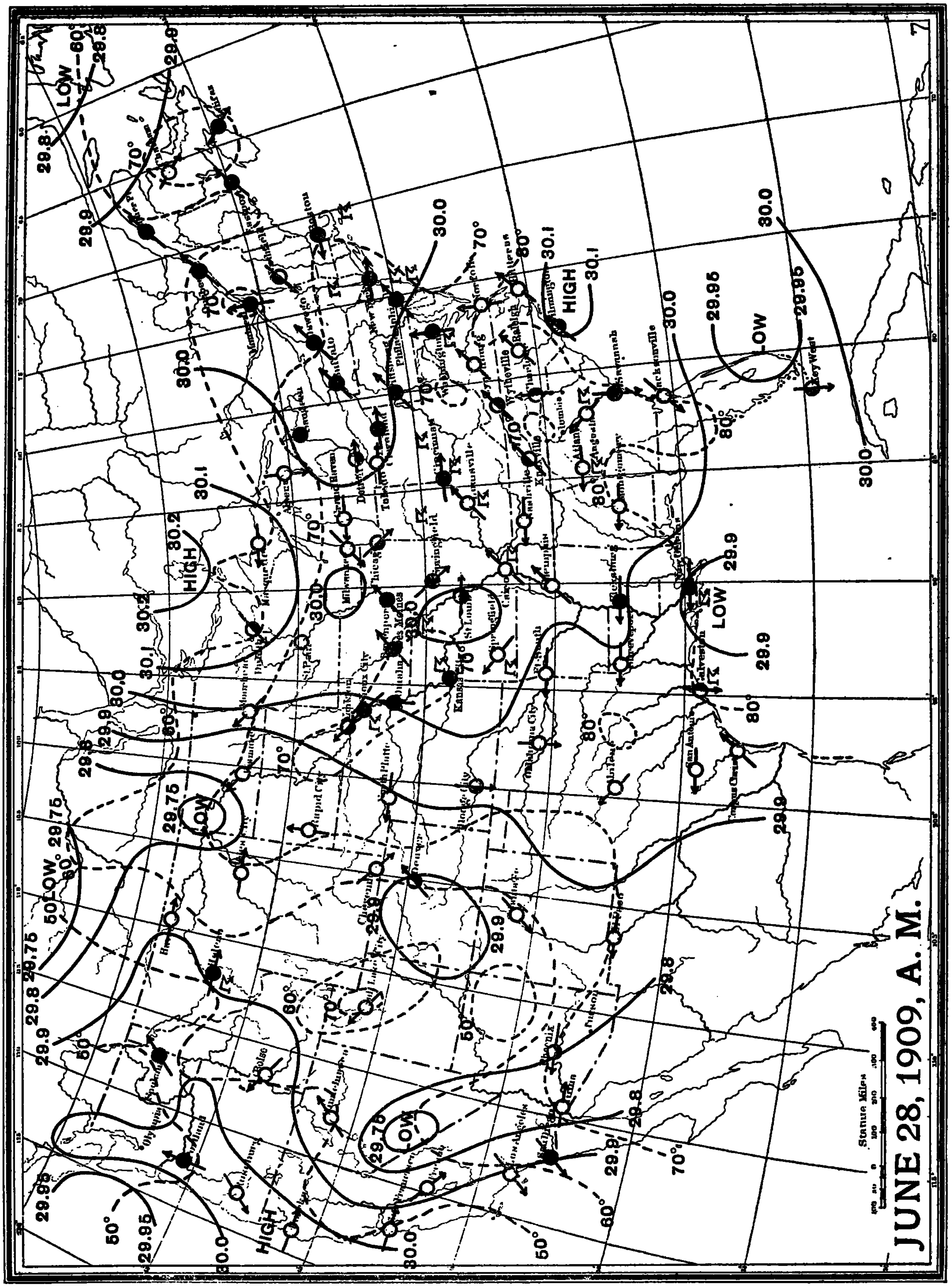

FIG. 7.—Weather Map, 8 a. m., June 28, 1909, typical of conditions at decline of "heat" thunderstorms. ○ clear; ◐ partly cloudy; ● cloudy; R rain; ⩚ thunderstorm.

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conditions, the second the particular pressure-temperature distribution in question, and the third the 12-hour subsequent conditions.

In these figures the isobars, in corrected inches of mercury, and the isotherms, in Fahrenheit degrees, are marked by full and by dotted lines, respectively. The legend "LOW" is written over a region from which, for some distance in every horizontal direction, the pressure increases. Similarly, the legend "HIGH" applies to a region from which, in every direction, the pressure decreases. The arrows, as is customary on such maps, fly with the wind, while the state of weather is indicated by the usual U. S. Weather Bureau symbols.

Obviously, the key to the geographic distribution of thunderstorms, vertical convection of humid air, is also the key to their location with reference to the existing distribution of barometric pressure. From this standpoint the places of their most frequent occurrence are:

a. Regions of high temperature and widely extended nearly uniform pressure. (See figs. 5, *6*, and 7.)

The conditions are still more favorable when the air is humid and the pressure, perhaps because of the humidity, slightly below normal or, at most, but little above normal.

When the pressure is approximately uniform the winds are light and every opportunity is given for the surface air to become strongly heated and thereby finally to establish thunderstorm convections. Such storms, always favored by mountain regions, and particularly by steep mountain peaks and strongly heated valleys, are, of course, most frequent of summer afternoons and are especially liable to occur at the end of two or three days of unusually warm weather. They develop here and there sporadically, hence the name "*local*" thunderstorm; last, as a rule, only an hour or two, and travel neither rapidly nor far. Those that form over mountain peaks often do not travel at all. The necessary initial convection is essentially, if not wholly, due to surface heating and therefore they frequently are referred to as "*heat*" thunderstorms. They are well-nigh the only type of thunderstorm in the tropics, and, perhaps, the most common type in the warmer portions of the temperate zones.

b. The southeast quadrant (Southern Hemisphere, northeast), or, less frequently, the southwest (Southern Hemisphere, northwest), of a regularly formed low, or typical cyclonic storm. (See figs. 8, *9*, and 10.)

In this case the temperature gradient essential to a rapid vertical convection is not produced chiefly by local surface heating, as it is during the genesis of "heat" thunderstorms, but, in great measure, results from the more or less crossed directions of the under and over currents of air. The surface air of the quadrant in question normally flows from lower and warmer latitudes, while with increasing altitude the winds come more and more nearly from the west, or even northwest. This crossing of the air currents, then, the lower from warmer sections and the upper from regions not so much warmer—possibly even colder—progressively increases the vertical temperature gradient, or rate of temperature decrease with increase of altitude, and therefore may frequently be, and doubtless often finally is, the determining cause of a rapid vertical convection and the formation of a thunderstorm.

This particular type of thunderstorm, commonly known as the "*cyclonic*" thunderstorm, is almost wholly confined to the temperate and higher zones, for the simple reason that the well-defined cyclone, essential to its creation, seldom occurs in tropical or equatorial regions.

c. The barometric valley between the branches of a distorted or V-shaped cyclonic isobar. (See figs. 11, *12*, and 13.)

This region is also favorable to the formation of secondary lows, which, though often of small area, sometimes are intense even unto tornadic violence.

Just how specific examples of this type of pressure distribution originated may not always be clear, but however established, each necessarily leads to opposing surface winds and also to more or less oppositely directed upper currents along adjacent paths; and each wind system, the lower and the upper, tends to produce an independent effect. Thus the opposing or conflicting surface winds cause such an irregular mixing of the air and such over and under running of currents as is likely to establish, here and there, a convection or thunderstorm gradient. Hence the frequency of thunderstorms along the valleys of low-pressure basins. On the other hand, the oppositely directed adjacent, not conflicting, upper currents by catching masses of air, especially rising masses, between them tend mechanically to produce, in the middle atmosphere, violent vortices of limited extent. The more violent of these vertical atmospheric whirls, usually accompanied by thunder and rain and often extending down to the surface of the earth, where they become destructive, are known as tornadoes. Hence thunderstorms generated in the barometric region under discussion, the region in which tornadoes most frequently originate and develop, might properly be called "*tornadic*" thunderstorms.

Atmospheric conflicts and turmoil, of the nature just described, obviously may occur at any place along the protrusion, or valley, of the low-pressure basin, and therefore often do occur, even simultaneously, here and there, along its entire length, and together form the well-known "line squall." Besides, as the whole cyclonic condition moves forward in general from west to east, maintaining, in a measure, for many hours its identity of form and nature, it follows that its valley of low pressure, and therefore its line of thunderstorms, must also travel with it in the same general direction and with approximately the same velocity.

A line or row of thunderstorms—a "line squall"—as observations show, always moves across its own axis, not necessarily at right angles, but nevertheless across and not parallel to it, nor even approximately so. The chief reason for this is not the axial direction of the low-pressure valley which, indeed, though usually *running* south, *may* have any orientation from the parent basin, but rather the fact that the valley itself, together with its accompanying thunderstorm conditions, travels across and not along its own direction.

In this connection it is also worth noting that the temperature distribution in the wake of a thunderstorm renders the occurrence of an immediate successor improbable, as will be explained later. Hence while a considerable number of thunderstorms may and often do travel abreast they can never follow each other closely in file.

d. The region covered by a low-pressure trough between adjacent high-pressure areas. (Figs. 14, *15*, and 16.)

Along the adjacent borders of two neighboring anticyclones—that is, along the barometric trough between them—the surface winds from one side are more or less directly opposed to those from the other. Hence, because of the overrunning, as explained under *c*, and the resulting temperature gradients, this also is a region of frequent thunderstorms. Here, too, a number of more or less independent storms may exist simultaneously along the same line, and advance abreast for great distances across the country.

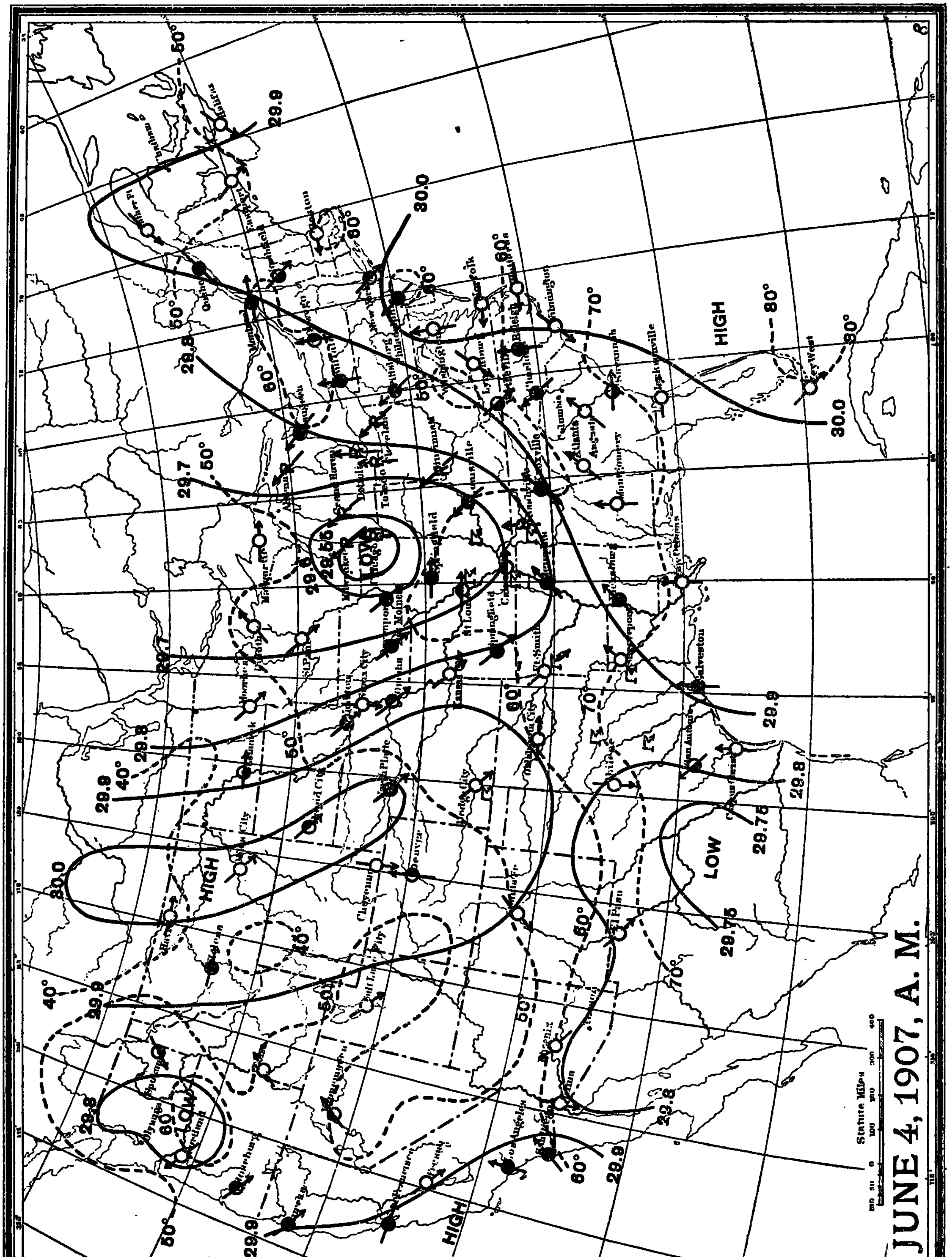

FIG. 8.—Weather Map, 8 a. m., June 4, 1907, typical of conditions at beginning of "cyclonic" thunderstorms. ○ clear; ◐ partly cloudy; ● cloudy; R rain; ⊠ thunderstorm.

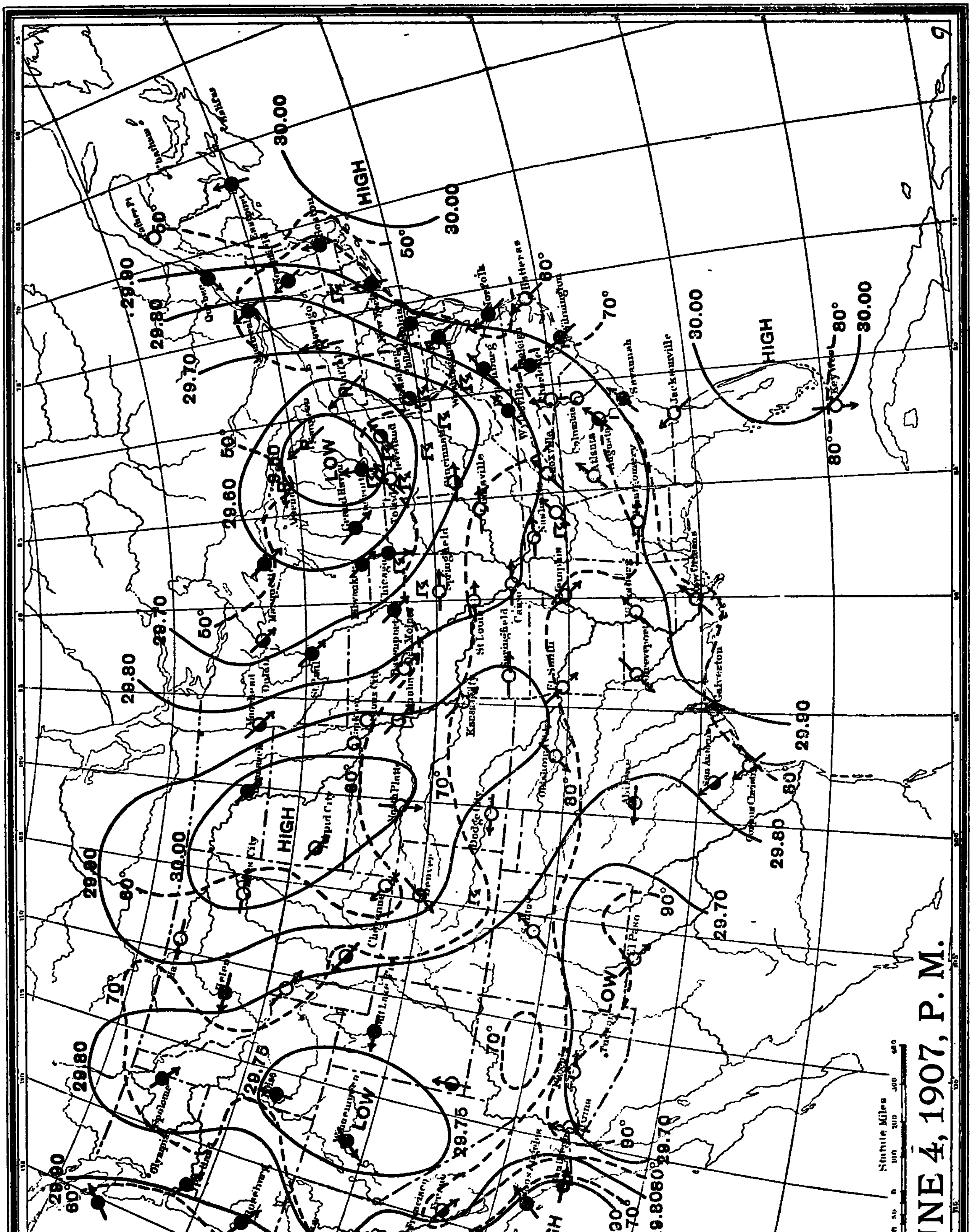

FIG. 9.—Weather Map, 8 p. m., June 4, 1907, typical of "cyclonic" thunderstorms. ○ clear; ◐ partly cloudy; ● cloudy; R rain; ⊠ thunderstorm.

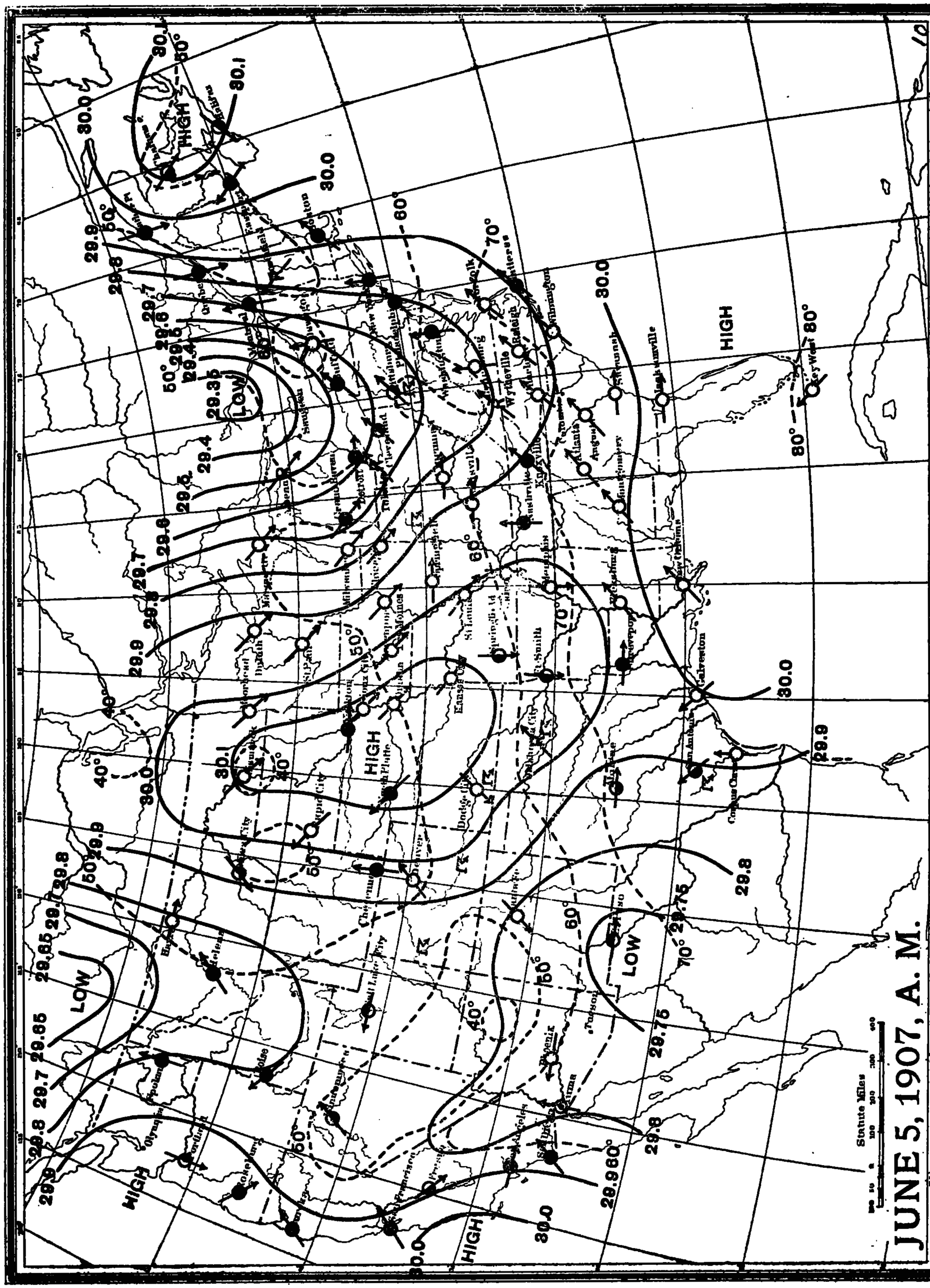

FIG. 10.—Weather Map, 8 a. m., June 5, 1907, typical of conditions at decline of "cyclonic" thunderstorms. ○ clear; ◐ partly cloudy; ● cloudy; R rain; ⛈ thunderstorm.

There does not appear to be any independent or distinctive name for the thunderstorm generated under this type of pressure distribution. Perhaps it might, with some justification, be called the "*anticyclonic*" thunderstorm, or even the "*trough*" storm.

e. The boundary between warm and cold waves. (See figs. 17, *18*, and 19.)

Along such a boundary the direction of flow of the warm humid layers of air is more or less opposite, as shown on the maps, to that of the colder ones. Therefore it must frequently happen that at irregular intervals along such a boundary the upper air, coming from the cold area, overruns a section of surface air belonging to the warm region; but, of course, only where the upper air is still potentially warmer than the lower—if potentially colder it would underrun. Now, wherever this overrunning on the part of the cold air does occur the vertical temperature gradient obviously is abruptly and greatly increased, and wherever, in the course of its further movement, the new gradient exceeds the adiabatic rate of temperature change, as analogous to case *b*, it often must, under the given conditions, vertical convection with rain, thunder, and lightning is apt to occur. Hence, as stated, the boundary between warm and cold waves is another place favorable to the thunderstorm, which, under these conditions, possibly might be called the "*border*" storm.

The above five distinct types of weather conditions, together with their innumerable variations and combinations, probably include all that are distinctly favorable to the production of thunderstorms. Each tends to establish an adiabatic or even superadiabatic temperature gradient up to the cloud level—the one thing essential to the production of a strong vertical convection, the progenitor, as we have seen, of the thunderstorm.

Thunderstorm winds.—Shortly, say 20 minutes or so, before the rain of a thunderstorm reaches a given locality the wind at that place, which generally is light and from the south or southwest across the path of the storm, begins to die down to an approximate calm and to change its direction. When this change is complete, it blows for a few minutes, rather gently, directly toward the nearest portion of the storm front, and finally, as the rain is almost at hand, again, but this time abruptly and in rather violent gusts, away from the storm and in the same direction that it is traveling, a direction that usually differs appreciably from that of the original surface wind. Generally this violent gusty wind lasts through only the earlier portion of the storm, and then is gradually but rather quickly succeeded by a comparatively gentle wind that, though following the storm at first, frequently, after an hour or so, blows in the same general direction as the original surface wind.

The cause of the thunderstorm winds needs to be carefully considered if one would understand at all clearly the mechanism of the storm itself.

As already explained, this type of storm owes its origin to that vertical convection which results from a more or less superadiabatic temperature gradient. It is this gradient, no matter how established, whether by simple surface heating or by the over and under running of unequally heated layers of air, that permits, or rather forces, the production of the cumulus cloud in which and by the motions of which the electricity that characterizes the storm in question is generated.

Nevertheless, as everyone knows, the passage of a cumulus cloud overhead, however large, so long as no rain is falling from it, does not greatly affect the direction and magnitude of the surface wind—does not bring on any of the familiar gusts and other thunderstorm phenomena. Hence we must infer that somehow or other the rain is an important factor both in starting and in maintaining the winds in question, for they do not exist before the rain begins nor continue after it has ceased. On the other hand, it cannot be assumed that the rain is the whole cause of these winds, for they do not accompany other and ordinary showers, however heavy the downpour may be.

The actual course of events, illustrated by figure 20, taken from the records obtained at Washington, D. C., during the passage of the notable thunder squall of July 30, 1913, seems to be about as follows:

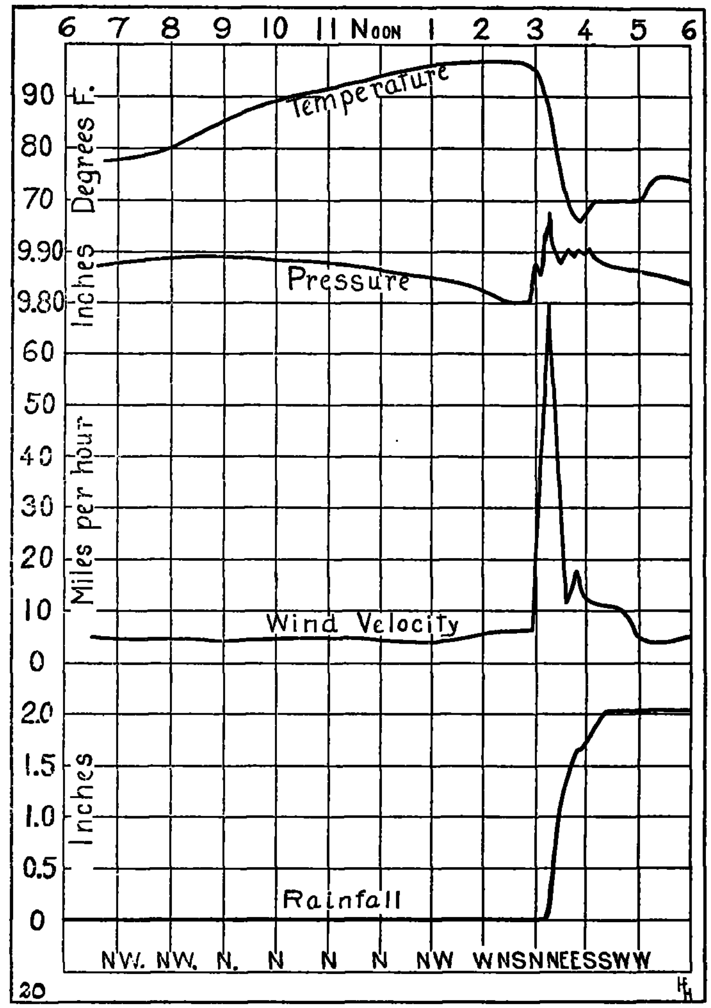

FIG. 20.—Course of meteorological elements on a thunderstorm day, at Washington, D. C. (July 30, 1913).

First. An approximately adiabatic temperature gradient is established over a wide area, roughly up to the base level of the cumulus clouds. But while the uprising branches of the existing convection currents, due to superadiabatic gradients, may be localized and here and there rather rapid, the return or downflow, though really the cause of the updraft, is widespread and correspondingly gentle. The condition essential to a local and rapid downflow—that is, a local decided cooling at a high altitude—does not exist, and therefore the counterpart to the upward currents is nowhere conspicuous.

Second. After a time, as a result of strong convection in a cumulus cloud, rain is formed at a considerable altitude where, of course, the air is quite cold, in fact so cold

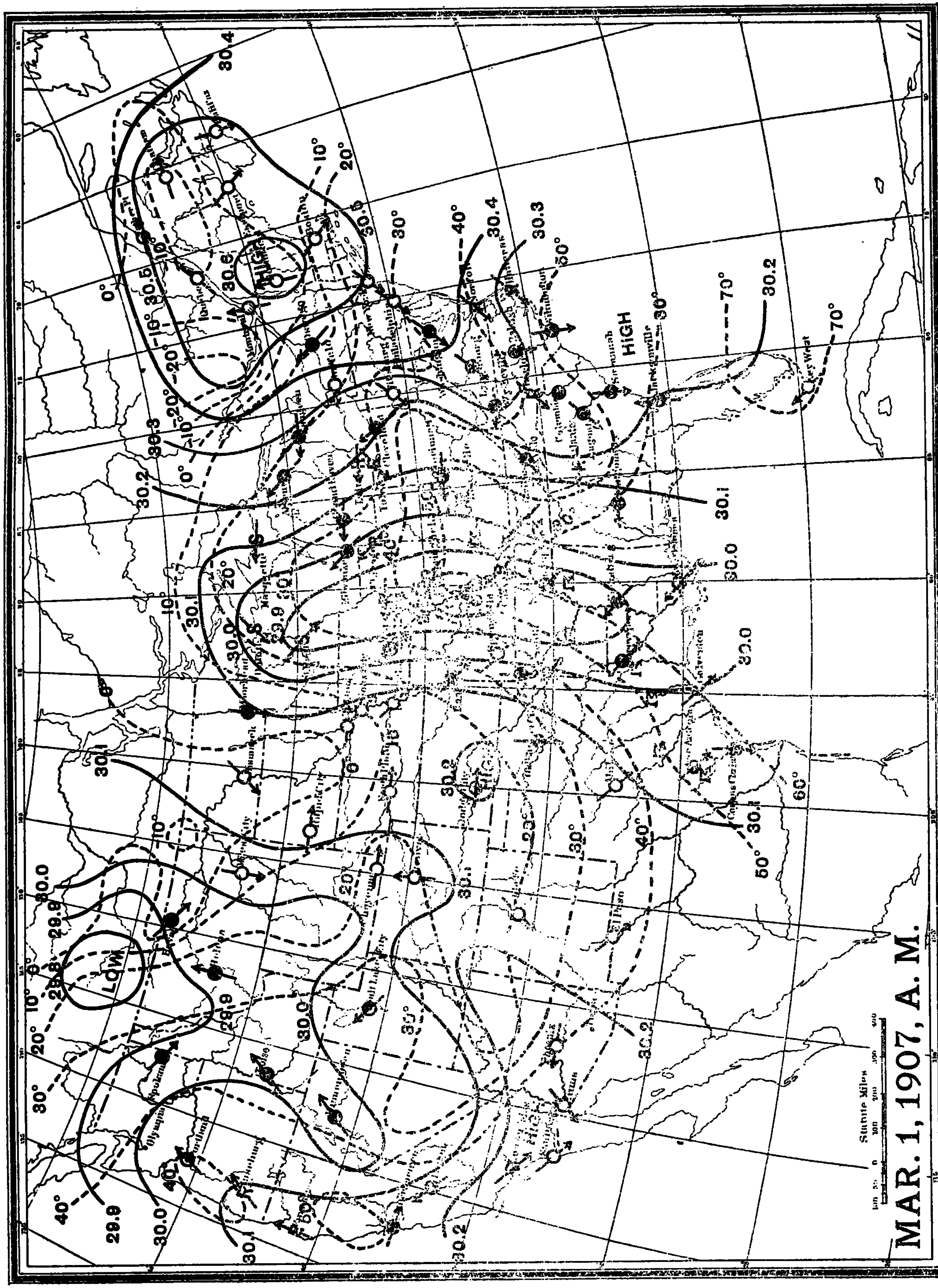

FIG. 11.—Weather Map, 8 a. m., March 1, 1907, typical of conditions at beginning of "tornadic" thunderstorms. ○ clear; ◐ partly cloudy; ● cloudy; R rain; ☈ thunderstorm.

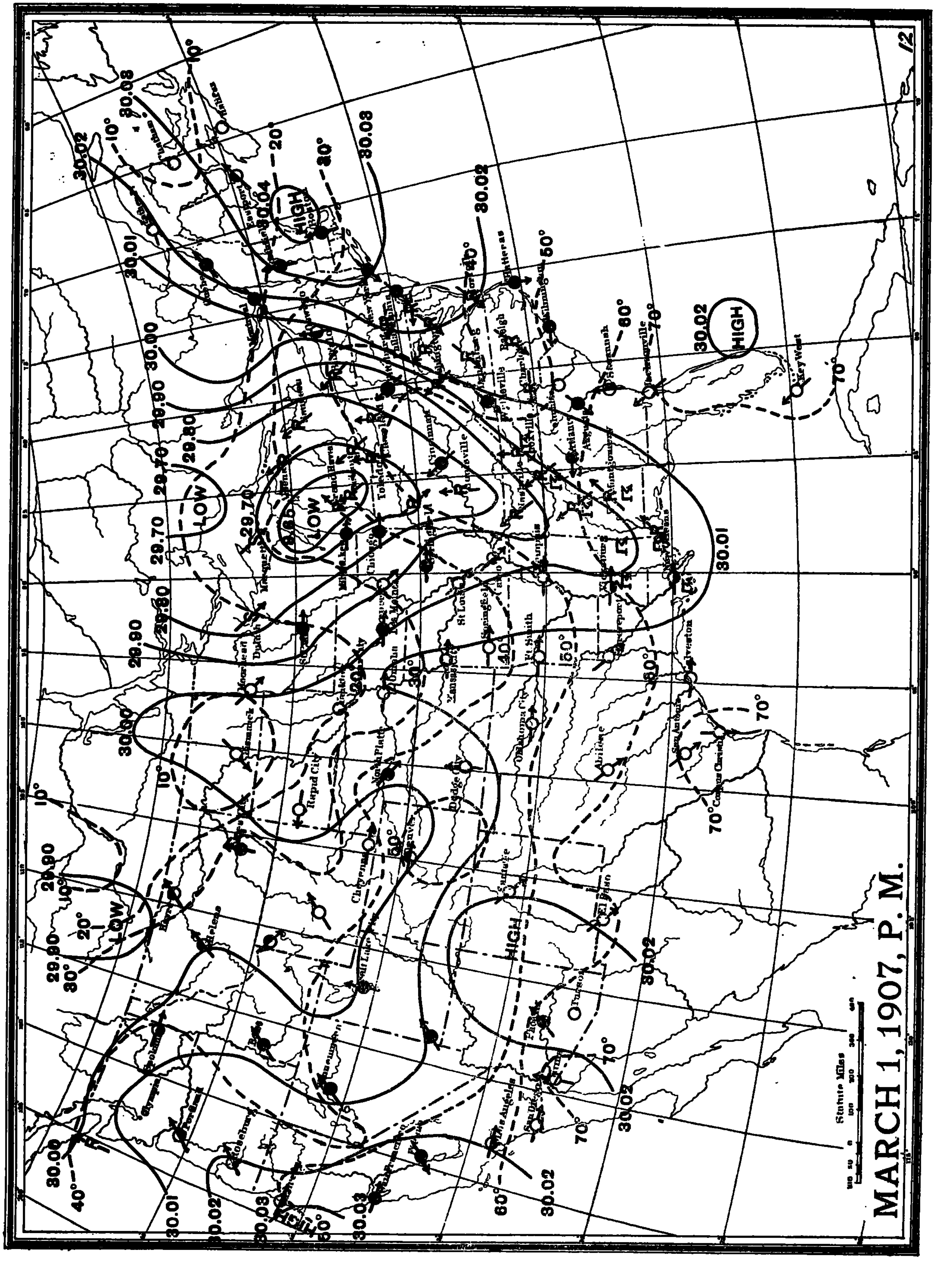

FIG. 12.—Weather Map 8 p. m., March 1 1907, typical of "tornadic" thunderstorms. ○ clear; ◐ partly cloudy; ● cloudy; R rain; ⌐ thunderstorm.

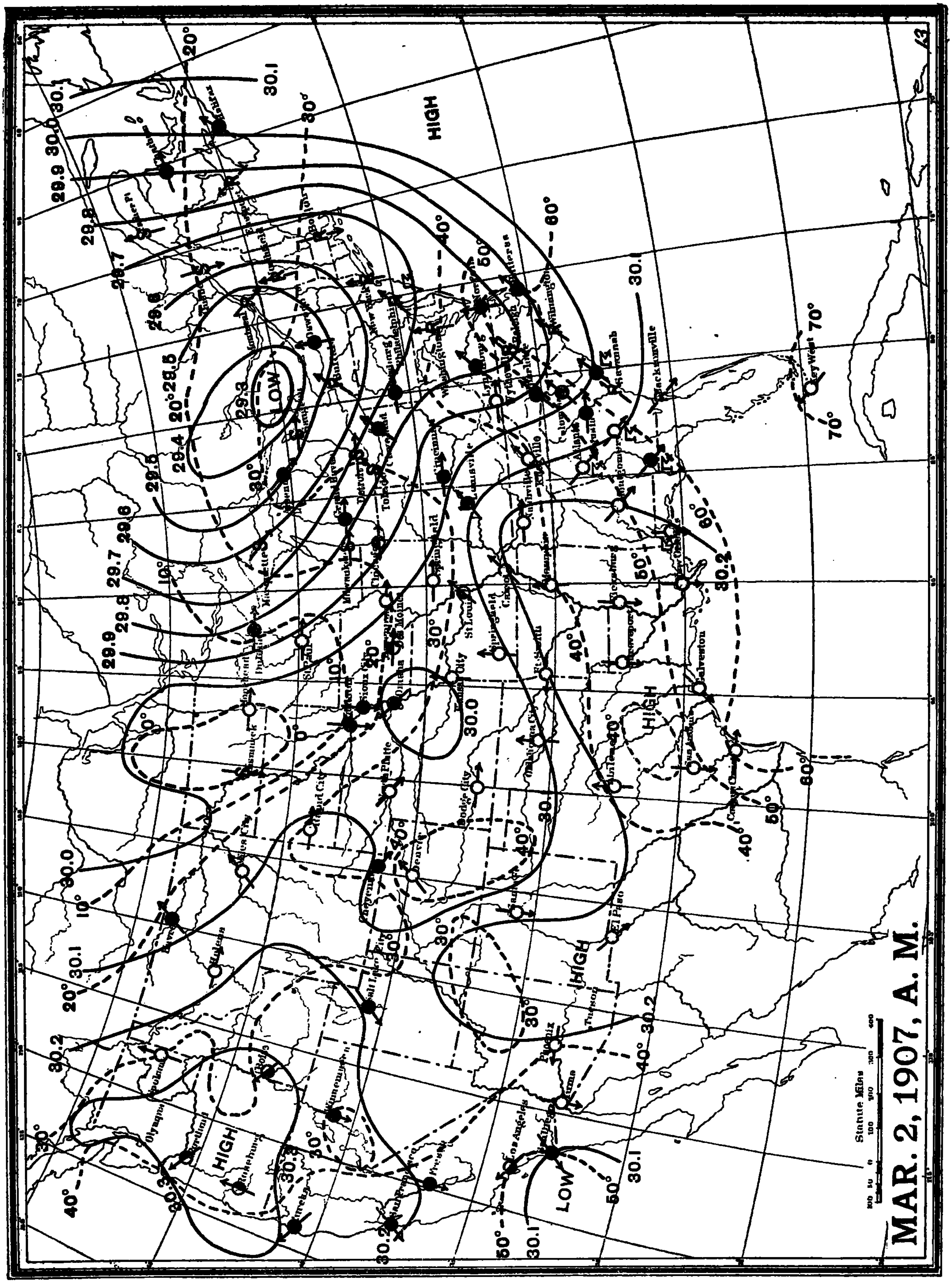

FIG. 13.—Weather Map, 8 a. m., March 2, 1907, typical of conditions at decline of "tornadic" thunderstorms. ○ clear; ◐ partly cloudy; ● cloudy; R rain; ⊓ thunderstorm.

that hail is often produced. Now this cold rain, or rain and hail, as it falls, and as long as it falls, chills the air from the level of its formation all the way to the earth, partly as a result of its initial low temperature and partly because of the evaporation that takes place during its fall. Hence this continuously chilled column of air because, somewhat, of the frictional drag of the rain, but mainly because of the increase, due to this chilling, of its own density, immediately and necessarily becomes a concentrated and vigorous, or swiftly flowing, return branch of the vertical circulation. In fact, it (or gravity acting through it) becomes the sustaining cause of the storm's circulation. At the same time, because of the downward blow and because of surface friction, as will be explained later, the barometric pressure is abruptly increased.

It will be worth while to consider some of these statements a little more closely, and to test them with possible numerical values.

Omitting, as we may, the effects of radiation, there seem to be but three possible ways by which the cooling of a thunderstorm may be obtained: *a*. By the descent of originally potentially cold air. *b*. By chilling the air with the cold rain. *c*. By evaporation. Each of these will be considered separately.

a. Obviously no portion of the upper air could maintain its position if potentially even slightly colder than that near the surface. If at all potentially colder it would fall until it itself became the surface air, as indeed is the case in all vertical circulation. Hence the great decrease in temperature that comes with a thunderstorm is not the result of the descent of a layer of air originally potentially cold for, as explained, an upper layer sufficiently cold to give, after its descent, the actual cooling could not exist. Again, any descending air must come from either below the under surface of the cloud or from above this level. If from below, it must, because of adiabatic heating, reach the earth at substantially the original surface temperature. If from above it would, as is obvious from figure 1, reach the earth even warmer than the original surface temperature. Hence, looked at in any way, case *a* obviously is inadmissible.

b. Let the under surface of the thunderstorm cloud be 1,500 meters above the earth, and the column of air cooled by the cold rain and its evaporation 2,000 meters high. Let the surface temperature be 30° C., and the temperature gradient before the storm begins adiabatic up to the under-cloud level, and let there be a 2-centimeter rainfall.

Now, at the temperature assumed, a column of air 2,000 meters high whose cross section is 1 square centimeter weighs, roughly, 210 grams, and its heat capacity, therefore, is approximately that of 50 grams of water. At the top of this column the temperature can be, at most, only about 20° C. lower than at the bottom, and if the rain leaves the top at this temperature but reaches the earth 7° C. colder than the surface air before the storm (temperatures that seem at least to be of the correct order) it will have been warmed 13° C. during its fall and the air column cooled on the average about 0.5° C. But, as a matter of fact, the air usually is cooled by from 5° C. to 10° C. Hence, while the temperature of the air necessarily is reduced to some extent by mere heat conduction to the cold rain much the greater portion of the cooling clearly must have some other origin. Further, since *a* is inadmissible and *b* only a minor contributing factor, it follows that by exclusion only evaporation, is left to account for much the greater portion of the cooling. Let us see, then, if evaporation really is adequate to meet these demands.

c. It is a common thing in semiarid regions to see a heavy shower, even a thundershower, leave the base of a cloud and yet fail utterly, because of evaporation, to reach the surface of the earth. Hence it appears quite certain that in the average thunderstorm a considerable portion of the rain that leaves the cloud is evaporated before it reaches the ground, and therefore that the temperature decrease of the atmosphere is largely owing to this fact. But if so, why, then, one might properly ask, does not an equally great temperature drop accompany all heavy rains?

The answer is obvious, because, as a rule, the temperature is higher and the relative humidity lower during a thunderstorm than at the time of any other ordinary rain. The chief, perhaps the sole, reason for this difference in relative humidity is the difference in the two cases, between the movements of the air. In the thunderstorm the descending air, which can be no more than saturated at top, dynamically warms so rapidly and is so continuously renewed that evaporation into it can not keep pace with its vapor capacity. During other rains, however, where there is no atmospheric descent, and therefore no dynamical heating, approximate saturation must soon obtion; hence but little further evaporation and, of course, but little cooling.

We will now return to the numerical values and compute a probable magnitude of cooling due to evaporation.

As before, let a 2-centimeter rain leave the cloud, but let one-fourth of the rain that started, or half a centimeter, be evaporated. This would consume 303 heat units from an air column 2,000 meters high whose heat capacity is that of only 50 cubic centimeters of water. Hence, as a result of evaporation alone, the temperature of the air column would be lowered on the average by about 6° C. Evaporation, therefore, appears to be both necessary and sufficient to produce all or nearly all the cooling of a thunderstorm.

Since the molecular weight of water is 18 while the average molecular weight of air is approximately 29, it follows that the amount of evaporation above assumed would decrease the density of the atmosphere by, roughly, one part in a thousand. On the other hand, a decrease in temperature of 6° C., that would be produced by the evaporation assumed, would increase the density by about one part in fifty. Hence the resultant of these two opposing effects is substantially that of the second alone; that is, a distinct increase in the density.

Doubtless, as already stated, the evaporation of thunderstorm rain, and therefore the drop in temperature and the consequent gain in density, all increase with decrease of elevation. In some measure, however, this effect is counteracted by the increasing rate of dynamical heating in the lower layers resulting from the correspondingly increased rate of pressure gain to change in elevation.

But no matter how nor to what extent the details may vary, it seems quite certain that the cold rain of a thunderstorm and its evaporation together must establish a local downrush of cold air—an observed important and characteristic phenomenon, really the immediate cause of the vigorous circulation, whose rational explanation has been attempted in the past few paragraphs.

As the column or sheet of cold air flows down it maintains in great measure its original velocity and, therefore, on reaching the earth rushes forward in the direction of the storm movement, underrunning and buoying up the adjacent warm air. And this condition, largely due, as explained, to condensation and evaporation, once established necessarily is self-perpetuating, so long as the general temperature gradient, humidity, and wind

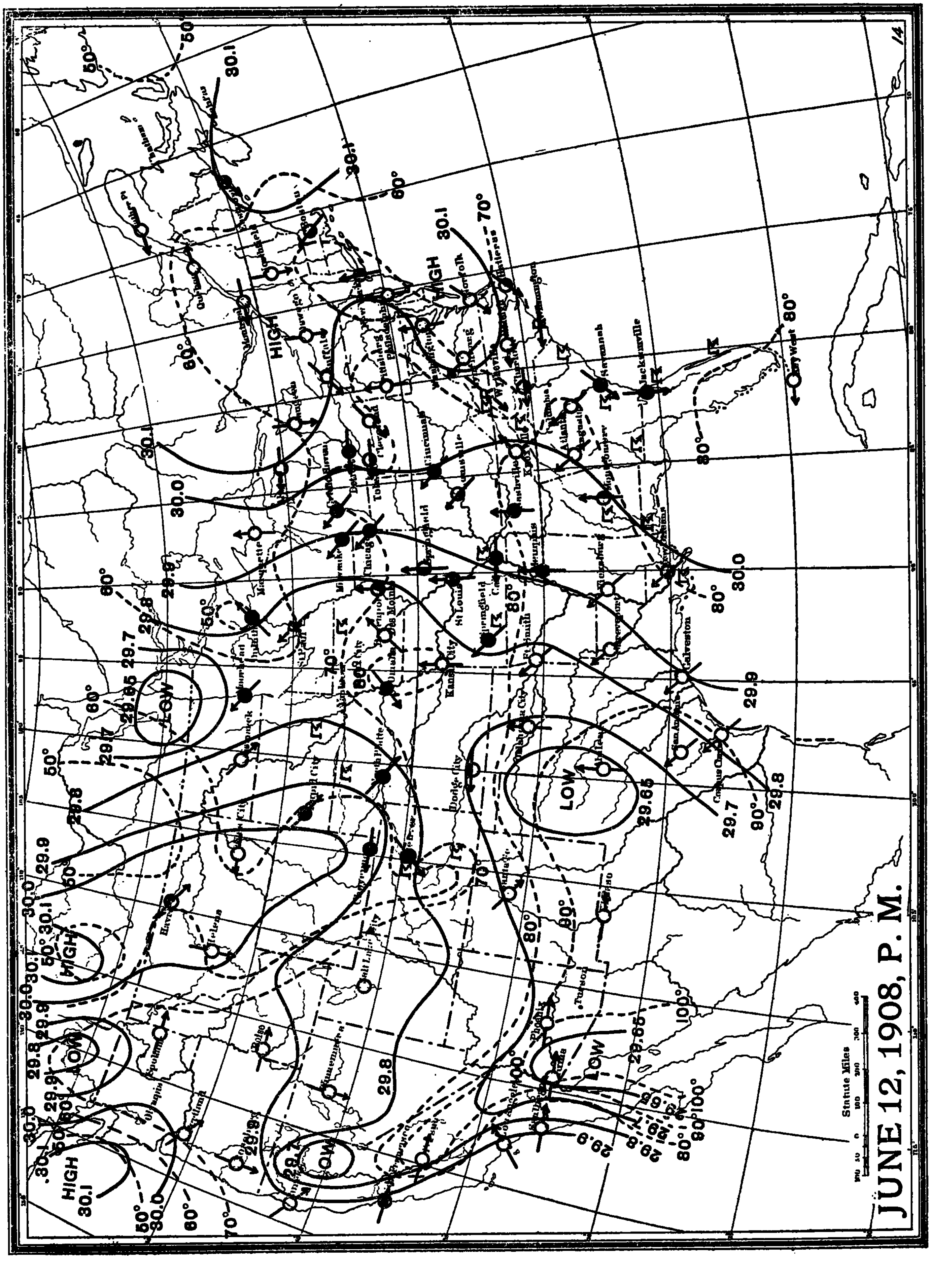

FIG. 14.—Weather Map, 8 p. m., June 12, 1908, typical of conditions at beginning of "trough" thunderstorms. ○ clear; ◐ partly cloudy; ● cloudy; R rain; ⌈⌊ thunderstorm.

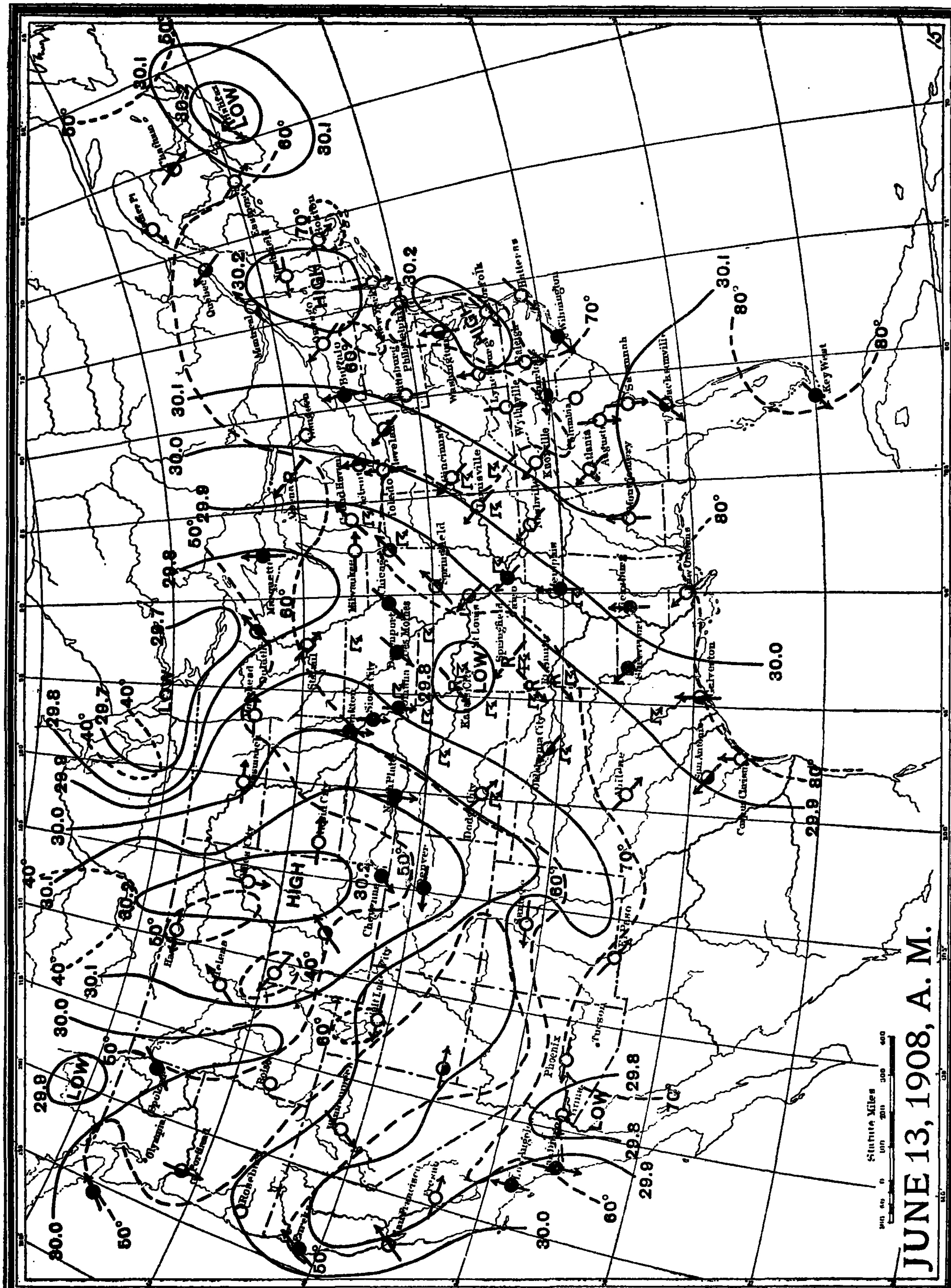

FIG. 15.—Weather Map, 8 a. m., June 13, 1908, typical of "trough" thunderstorms. ○ clear; ◐ partly cloudy; ● cloudy; R rain; ⌈Z thunderstorm.

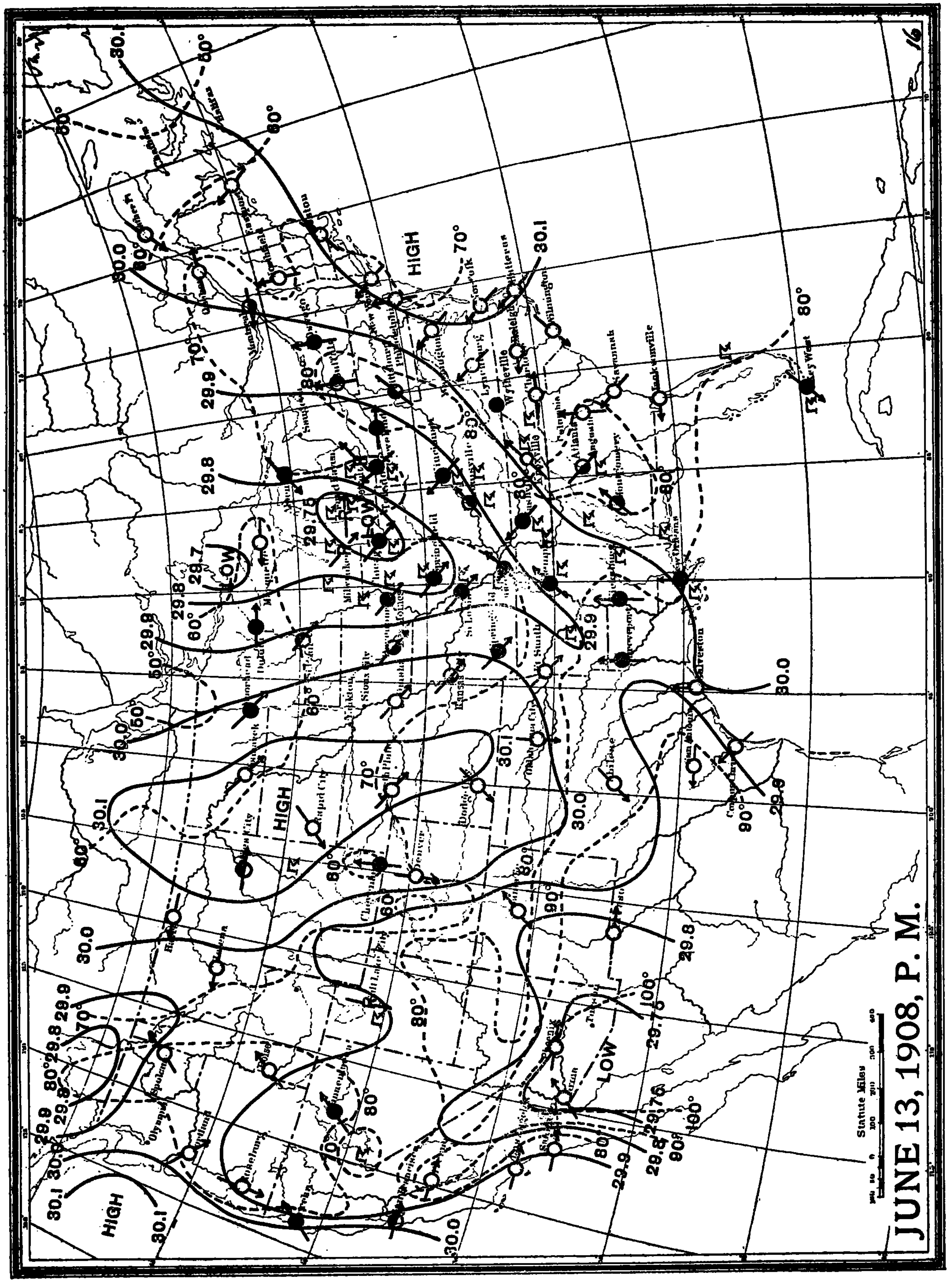

FIG. 16.—Weather Map, 8 p.m., June 13, 1908, typical of conditions at decline of "trough" thunderstorms. ○ clear; ◐ partly cloudy; ● cloudy; R rain; ⊼ thunderstorm.

direction are favorable. It must be remembered, however, that thunderstorm convection, rising air just in front and descending air with the rain, does not occur in a closed circuit, for the air that goes up does not return nor does the air that comes down immediately go up again, there simply is an interchange between the surface air in front of the storm and the upper air in its rear. The travel of the storm, by keeping up with the underrunning cold current, just as effectually maintains the temperature contrast essential to this open-circuit convection as does continuous heating on one side and cooling on the other maintain the temperature contrast essential to a closed circuit convection.

The movements of the warm air in front of the rain, the lull, the inflow, and the updraft resemble somewhat those of a horizontal cylinder resting on the earth where the air is quiet and rolling forward with the speed of the storm. Similarly, the cold air in its descent and forward rush, together with the updraft of warm air, also resembles a horizontal cylinder, but one sliding on the earth and turning in the opposite direction from that of the forward rolling or all-warm cylinder. In neither case, however, is the analogy complete, for, as above explained, the air that goes up remains aloft while the cold air that comes down is kept by its greater density to the lower levels. The condition of flow persists, as do cataracts and crest clouds, but here, too, as in their case, the material involved is ever renewed.

The squall cloud.—Between the uprising sheet of warm air and the adjacent descending sheet of cold air horizontal vortices are sure to be formed in which the two currents are more or less mixed. The lower of these vortices can only be *inferred* as a necessary consequence of the opposite directions of flow of the adjacent sheets of warm and cold air, for there is nothing to render them visible. Neither can any vortices that may exist within the cloud be seen. Near the front lower edge of the cumulo-nimbus system, however, and immediately in front of the sheet of rain, or rain and hail, the rising air has so nearly reached its dew point that the somewhat lower temperature, produced by the admixture of the descending cold air, is sufficient to produce in it a light foglike condensation which, of course, renders any detached vortex at this position quite visible.

This squall cloud, in which the direction of motion on top is against the storm, may be regarded as a third horizontal thunderstorm cylinder much smaller but more complete than either of the others.

Schematic illustrations.—The above conceptions of the mechanism of a thunderstorm can, perhaps, be made a little clearer with the aid of illustrations. Figure 21, a schematic picture of a thunderstorm in the making, gives the boundary of a large cumulus cloud from which rain has not yet begun to fall, and the stream lines of atmospheric flow into it. When the cloud is stationary and there is no surface wind the updraft obviously will be more or less symmetrical about a vertical through its center, but when it has an appreciable velocity, as indicated in the figure, it is equally obvious that most, often nearly all, of the air entering the cloud will do so through its front under-surface. At this stage there will be no concentrated or local down current, only an imperceptible counter settling of the air round about, because, as previously explained, the air cataract requires local cooling to subpotential temperatures, and this in turn requires local rain.

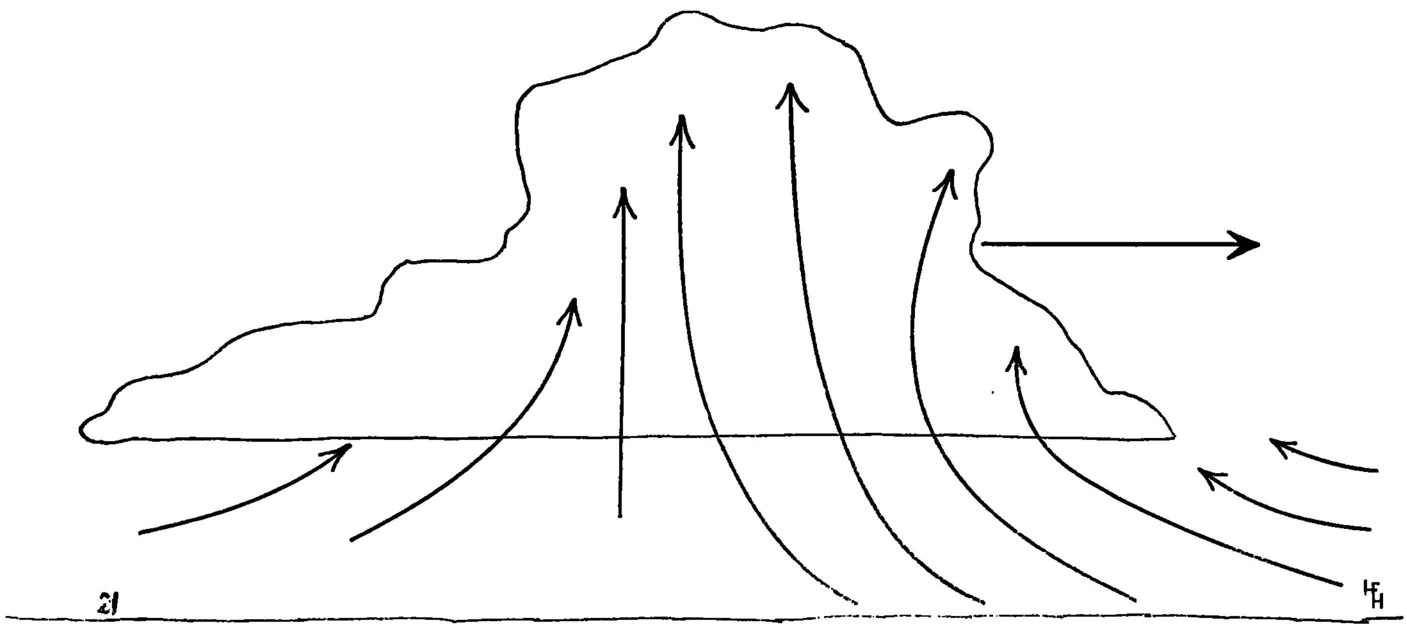

FIG. 21.—Principal air movements in the development of a cumulus cloud.

Figure 22 schematically represents a well-developed thunderstorm in progress. The falling rain, often mixed with hail, cools the air through which it falls, and as the temperature gradient was already closely adiabatic it follows that the actual temperatures will be subpotential from the surface of the earth to within the cloud, or throughout and a little beyond the nonsaturated or evaporating levels. As soon, then, as this column or sheet of air is sufficiently cooled it flows down and forward and all the atmospheric movements peculiar to the thunderstorm are established substantially as shown.

Referring to the figure: The warm ascending air is in the region A; the cold descending air at D; the dust cloud (in dry weather) at D′, the squall cloud at S; the storm collar at C; the thunder heads at T; the hail at H; the primary rain, due to initial convection, at R; and the secondary rain at R′. This latter phenomenon, the secondary rain, is a thing of frequent occurrence and often is due, as indicated in the figure, to the coalescence and quiet settling of drops from an abandoned portion of the cumulus in which and below which winds and convection are no longer active.

Mammato-cumuli rarely, false cirri frequently, and cap-clouds occasionally, accompany thunderstorms, but as they are not essential to it they therefore are omitted from the above schematic illustration.

Thunderstorm pressures.—Before the onset of a thunderstorm there usually if not always is a distinct fall in the barometer. At times this fall is extended over several hours, but whether the period be long or short the rate of fall usually is greatest at the near approach of the storm. Just as the storm breaks, however, the pressure rises very rapidly, almost abruptly, usually from 1 to 2 millimeters, fluctuates irregularly, and finally as the storm passes again becomes rather steady but at a somewhat higher pressure than prevailed before the storm began.

The cause of these pressure changes is, doubtless, rather complex. The decrease in the absolute humidity and the decrease in temperature both tend to increase the atmospheric pressure, and, presumably, each contributes its share. Both these effects, however, are comparatively permanent, and while they may be mainly responsible for the increase of pressure that persists after the storm has gone by, they probably are not the chief factors in the production of the initial and quickly produced pressure maximum. Here at least two factors, one obvious, the other inconspicuous, are involved. These are: *a*. The rapid downrush of air, and *b*. the interference to horizontal flow caused by the vertical circulation.

The downrush of air clearly produces a vertically directed pressure on the surface of the earth, in the same manner that a horizontal flow produces a horizontally directed pressure against the side of a house. But a pressure equal to that given by 2 mm. of mercury, a pressure increase frequently reached in a thunderstorm, would mean about 2.72 grams per square centimeter, or 27.2 kilograms per square meter, and require a wind velocity of roughly 50 kilometers per hour or 14 meters per second. Now, the velocity of the downrush of air in a thunderstorm is not at all accurately known, but while at times probably very considerable, the above value of 14 meters per second seems to be excessive; in fact, its average value may not be even half so great. If in reality it is not, then, since the pressure of a wind varies as the square of its velocity, it follows that less than one-fourth of the actual pressure increase can be caused in this way. Hence it would seem that there probably is at least one other pressure factor, and, indeed, such a factor obviously exists in the check to the horizontal flow caused by vertical convection.

To make this point clear: Assume two layers of air, an upper and a lower, flowing parallel to each other. Let their respective masses per unit length in the direction of their horizontal movement be M and m, and their velocities V and v. Now, if, through convection, say, the whole or any portion of the lower layer is carried aloft, obviously it must be replaced below by an equal amount of the upper layer.

Let the whole of the lower layer be carried up. This layer, to produce the rain that was above assumed, 2 centimeters, will have to be at least 1 kilometer deep, and if it should merely change places with the upper air, or if the different layers should mingle and assume a common velocity, V', there obviously would be no change in the total linear momentum, nor in the flow. In symbols we would have the equation

$$MV+mv=(M+m)\ V'.$$

Mere mingling, therefore, of the two air currents, upper and lower, can not change the depth of the atmosphere, nor, therefore, the height of the barometer. But then in the case of atmospheric convection we have something more than the simple mingling of two air currents, and the linear momentum does not, in general, remain constant. The increased surface velocity following convection, a phenomenon very marked in the case of a thunderstorm, causes an increased frictional drag and therefore a greater or less decrease in the total flow. Suppose this amounts to the equivalent of reducing the velocity of a layer of air only 25 meters thick from V to v, and let $V=5v$. That is, the one three hundred and twentieth part of the atmosphere has its flow reduced to

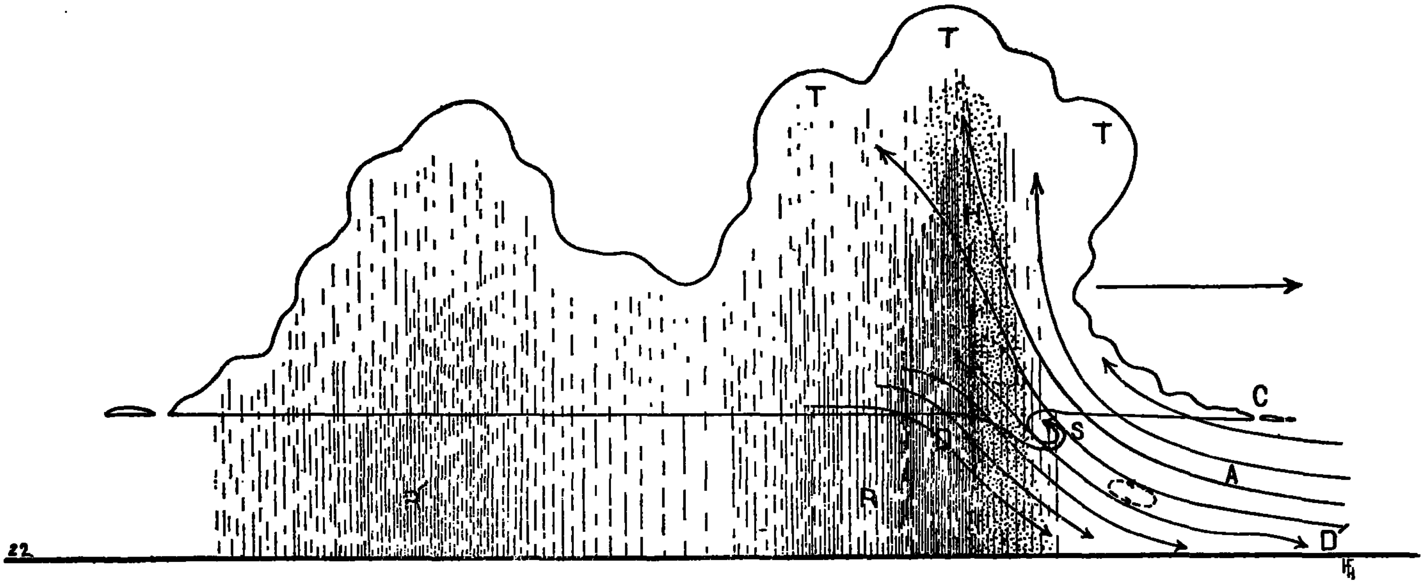

FIG. 22.—Ideal cross section of a typical thunderstorm. A ascending air, D descending air, C storm collar (Sturmkragen), S roll scud, D' wind gust, H hail, T thunderheads, R primary rain, R' secondary rain.

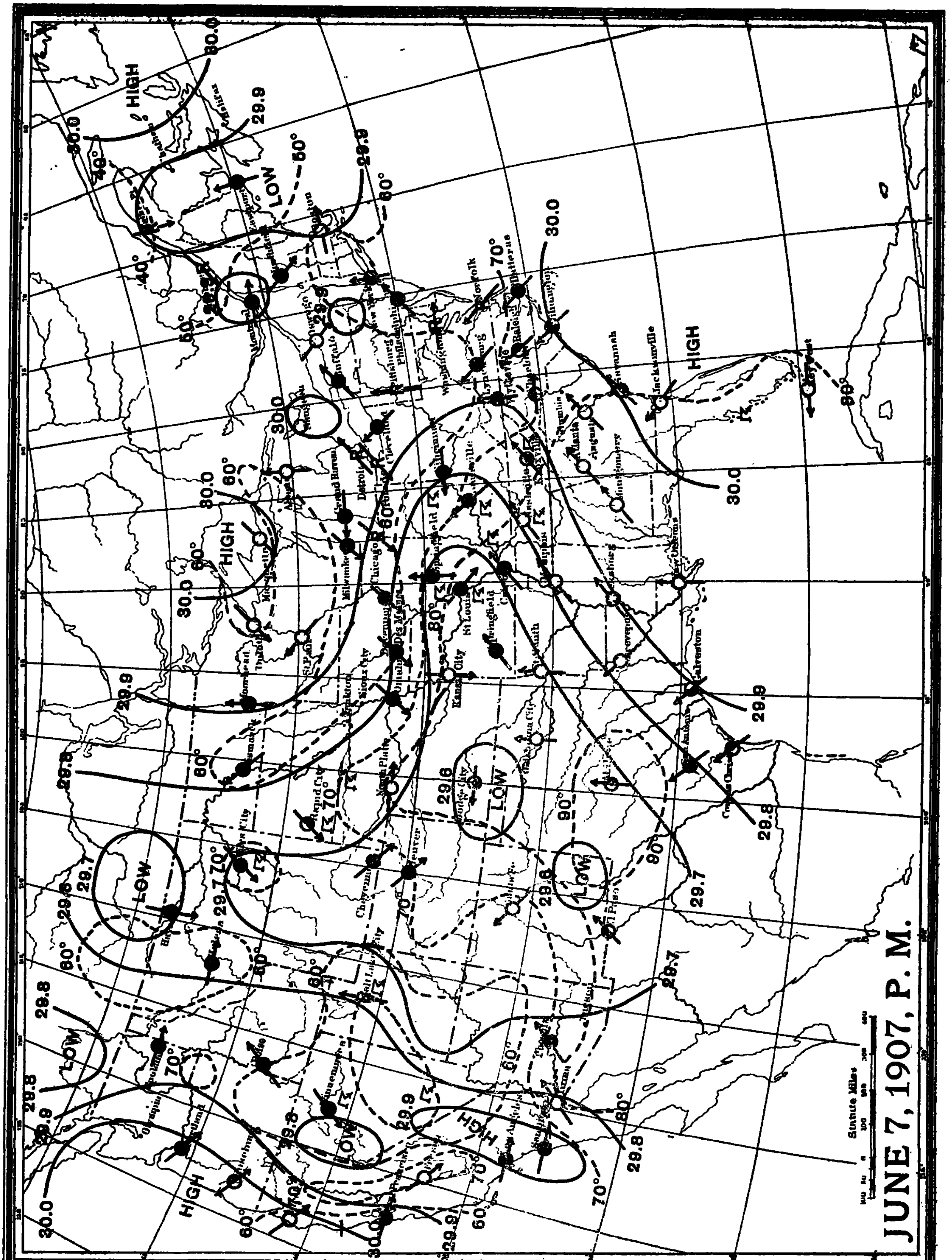

FIG. 17.—Weather Map, 8 p. m., June 7, 1907, typical of conditions at beginning of "border" thunderstorms. ○ clear; ◐ partly cloudy; ● cloudy; R rain; ⊠ thunderstorm.

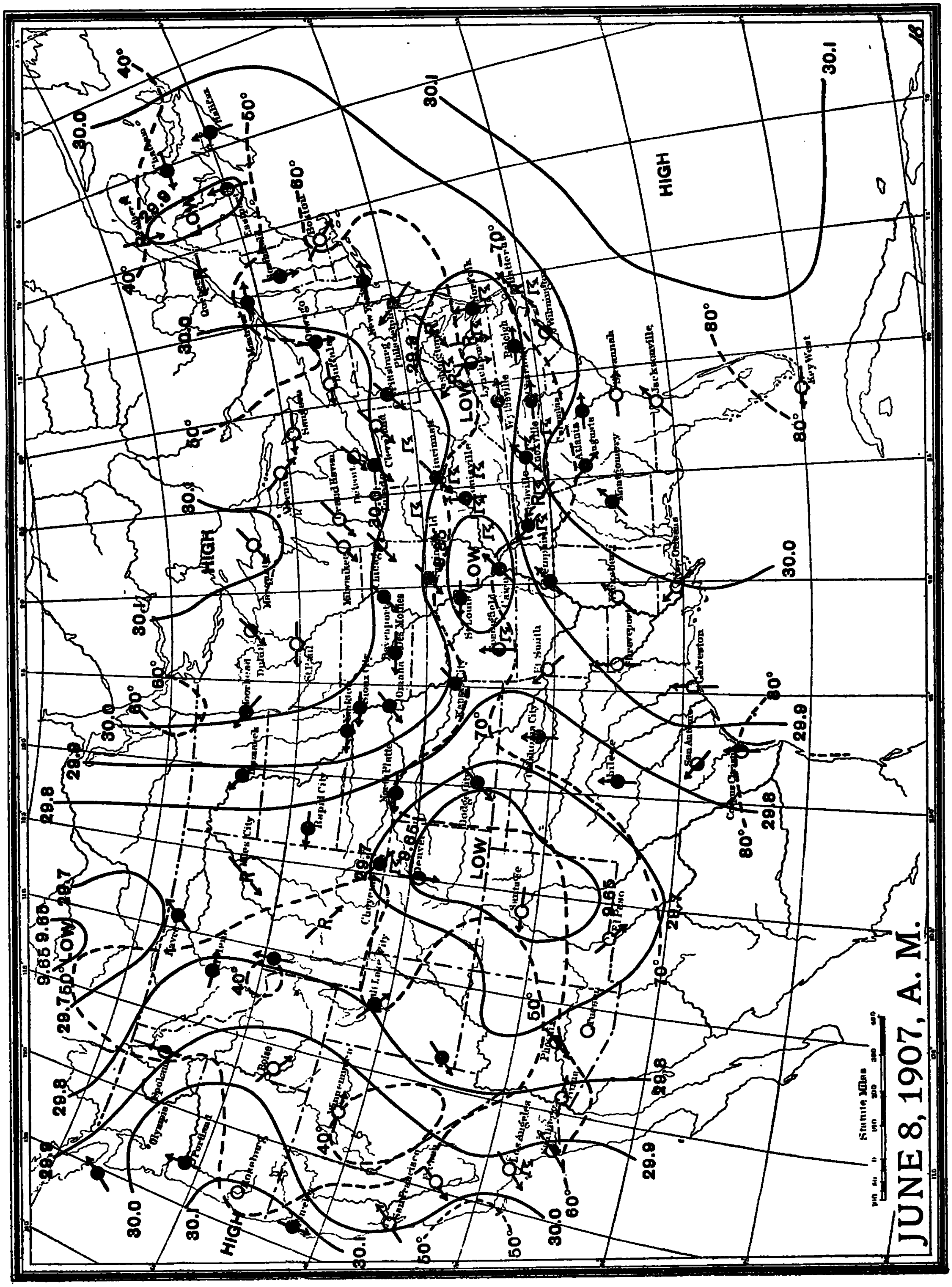

FIG. 18.—Weather Map, 8 a. m., June 8, 1907, typical of "border" thunderstorms. ○ clear; ◐ partly cloudy; ● cloudy; R rain; ⛈ thunderstorm.

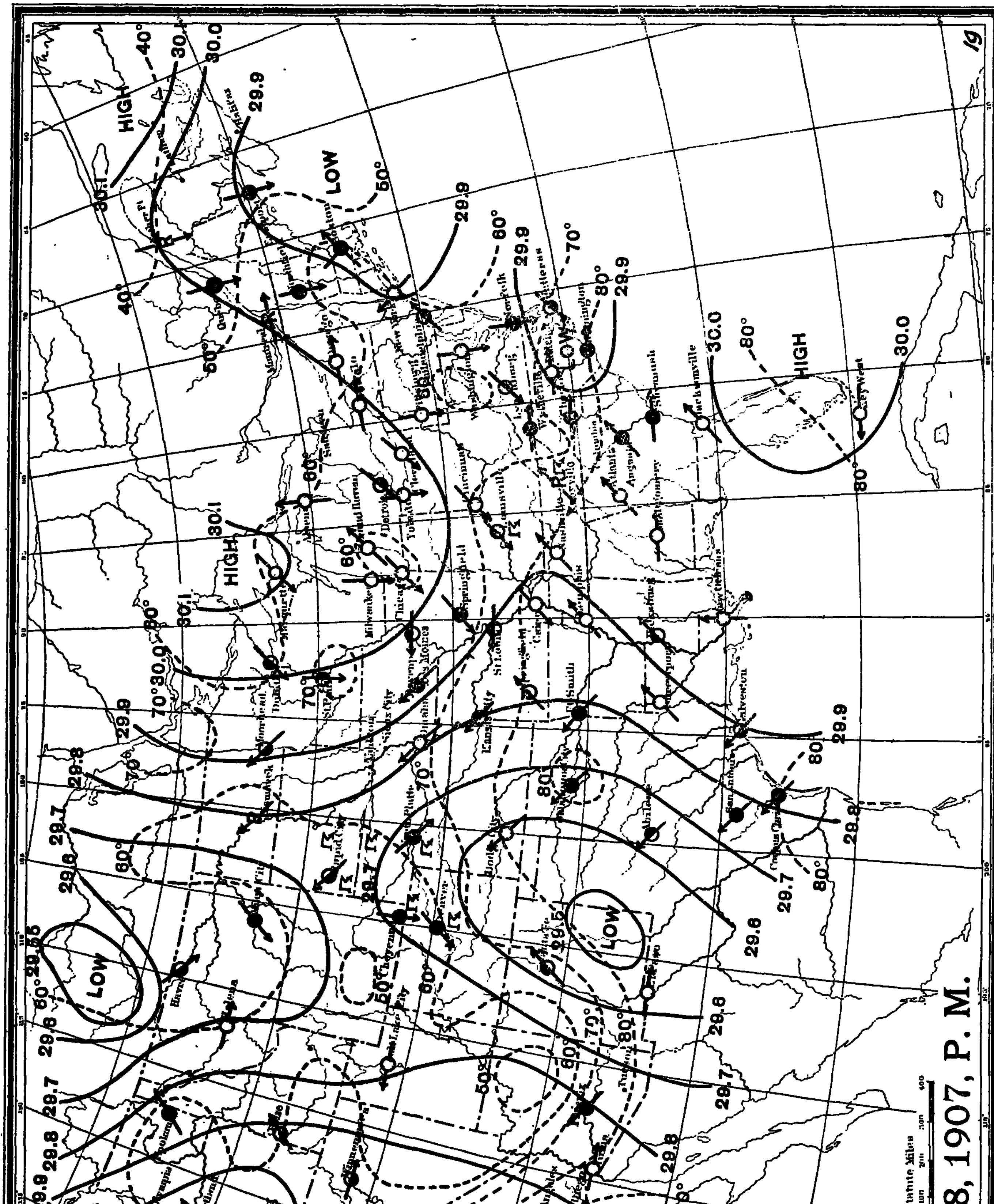

FIG. 19.—Weather Map, 8 p. m., June 8, 1907, typical of conditions at decline of "border" thunderstorms. O clear; ◐ partly cloudy; ● cloudy; R rain; ⩘ thunderstorm.

one-fifth its former value. This would reduce the total flow by about 1 part in 400, and thereby increase the barometric reading by nearly 2 millimeters.

It would seem, then, that the friction of the thunderstorm gust on the surface of the earth, through the consequent decrease in the total linear momentum of the atmosphere and, therefore, its total flow, must be an important contributing cause of the rapid and marked increase of the barometric pressure that accompanies the onset of a heavy thunderstorm.

To sum up: The chief factors contributing to the increase of the barometric pressure during a thunderstorm appear to be, possibly in the order of their magnitude: *a.* Decrease of horizontal flow, due to surface friction. *b.* Vertical wind pressure, due to descending air. *c.* Lower temperature. *d.* Decrease in absolute humidity.

Thunderstorm temperatures.—Before the onset of the storm the temperature commonly is high, but it begins rapidly to fall with the first outward gust and soon drops often as much as 5° C. to 10° C. because, as already explained, this gust is a portion of the descending air cooled by the cold rain and by its evaporation. As the storm passes the temperature generally recovers somewhat, though it seldom regains its original value.

Thunderstorm humidity.—As previously explained, heavy rain, at least up in the clouds, and therefore much humidity, and a temperature contrast sufficient to produce rapid vertical convection, are essential to the genesis of a thunderstorm. Hence during the early forenoon of a thunderstorm day both the absolute and the relative humidity are likely to be high. Just before the storm, however, when the temperature has greatly increased, though the absolute humidity still is high, the relative humidity is likely to be rather low. On the other hand, during and immediately after the storm, because chiefly of the decrease in temperature, the absolute humidity is comparatively low and the relative humidity high.

"Rain-gush."—It has frequently been noted that the rainfall is greatest after heavy claps of thunder, a fact that appears to have given much comfort and great encouragement to those who maintain the efficacy of mere noise to induce precipitation—to jostle cloud particles together into raindrops. The correct explanation, however, of this phenomenon seems obvious: The violent turmoil and spasmodic movements within a large cumulus or thunderstorm cloud cause similar irregularities in the condensation and resulting number of raindrops at any given level. These in turn, as broken by the air currents, give local excess of electrification and of electric discharge or lightning flash. We have, then, starting toward the earth at the same time and from practically the same level, mass, sound, and light. The light travels with the greatest velocity, about 300,000 kilometers per second, and therefore the lightning flash is seen before the thunder is heard; its velocity being, roughly, only 330 meters per second. But the rain falls much slower still and therefore reaches the ground after the thunder is heard. In reality it is the excessive condensation or rain formation up in the cumulus cloud that causes the vivid lightning and the heavy thunder. According only to the order in which their several velocities cause them to reach the surface of the earth it might appear, and has often been so interpreted, that the lightning, first perceived, was the cause of the thunder, which, indeed, it is, and that the heavy thunder, next in order, was the cause of the excessive rain, which most certainly it is not.

Thunderstorm velocity.—The velocity of the thunderstorm is simply the velocity of the atmosphere in which the bulk of the cumulus cloud happens to be located. Hence as the wind at this level is faster by night than by day and faster over the ocean than over land, it follows that exactly the same relations hold for the thunderstorm, that it travels faster over water than over land and faster by night than by day. The actual velocity of the thunderstorm, of course, varies greatly, but its average velocity in Europe is 30 to 50 kilometers per hour; in the United States, 50 to 65 kilometers per hour.

Hail.—Hail, consisting of lumps of roughly concentric layers of compact snow and solid ice, is a conspicuous and well-known phenomenon that occurs during the early portion of most severe thunderstorms. But in what portion of the cloud it is formed and by what process the layers of ice and snow are built up are facts that, far from being obvious, become clear only when the mechanism of the storm itself is understood.

As before, let the surface temperature be 30° C. and the absolute humidity 40 per cent, or the dew point 15° C. Under these conditions saturation will obtain, and, therefore, cloud formation will begin when the surface air has risen to an elevation of 1.5 kilometers. Immediately above this level the latent heat of condensation reduces the rate of temperature decrease with elevation to about half its former value, nor does this rate rapidly increase with further gain of height. Hence, usually, for the above assumptions correspond in general to average thunderstorm conditions, it is only beyond the 4-kilometer level that freezing temperatures are reached. It is therefore only in the upper portions of cumulus clouds, the portions that clearly must consist of snow particles and undercooled fog or cloud droplets, that hail can either originate or greatly grow.

But what, then, is the process by which the nucleus of the hailstone is formed and its layer upon layer of snow and ice built up? Obviously such drops of rain as the strong updraft within the cloud may blow into the region of freezing temperatures will quickly congeal and also gather coatings of snow and frost. After a time each incipient hailstone will get into a weaker updraft, for this is always irregular and puffy, or else will tumble to the edge of the ascending column. In either case it will then fall back into the region of liquid drops, where it will gather a coating of water, a portion of which will at once be frozen by the low temperature of the kernel. But again it meets an upward gust, or falls back where the ascending draft is stronger, and again the cyclic journey from realm of rain to region of snow is begun; and each time—there may be several—the journey is completed a new layer of ice and a fresh layer of snow are added. In general the size of the hailstones will be roughly proportional to the strength of the convection current, but since their weights vary approximately (they are not homogeneous) as the cube of their diameters while the supporting force of the upward air current varies, also approximately, as only the square of their diameters it follows that a limiting size is quickly reached. It is also evident, from the fact that a strong convection current is essential to the formation of hail, that it can occur only where this convection exists; that is, in the front portion of a heavy to violent thunderstorm.

Some meteorologists hold that the roll scud between the ascending warm and descending cold air is the seat of hail formation, but this is a mistaken assumption. Centrifugal force would throw a solid object, like a hailstone, out of this roll probably before a single turn had been completed. Besides, and this objection is, perhaps, more obviously fatal than the one just given, the temperature of the roll scud, because of its position, the lowest of the whole storm cloud, clearly must be many degrees above the freezing point. Indeed, as the above calculation shows, temperatures low enough for the formation of hail can not often obtain at levels much less than three times that of the scud, and therefore it clearly is in the higher levels of the cumulus and not in the low scud that hail must have its genesis and make its growth.

Lightning.—About the middle of the eighteenth century Franklin and others clearly demonstrated that the lightning of a thunderstorm and the discharge of an ordinary electric machine are identical in nature, and thereby established the fact that many of the properties of the former may logically be inferred from laboratory experiments with the latter. There is, however, one important source of difference between the two phenomena that does not seem always to be clearly kept in mind, namely, the distribution of the charge. In the one case, that of the laboratory experiment, the charge commonly exists almost wholly on the surface of the apparatus used, while in the other, that of the thunderstorm, it is irregularly distributed throughout the great cloud volume. Hence the two discharges, lightning and laboratory sparks, necessarily differ from each other in important details. Nevertheless in each case the atmosphere must be ionized before the discharge can take place freely, and this condition seems, at times at least, to establish itself progresso-spasmodically. That is, a small initial discharge, losing itself in a terminal brush, is rapidly followed by another and another, each losing itself in a manner similar to the first, until a path from pole to pole is sufficiently ionized to permit of a free flow and quick exhaustion of the remaining charge. Figure 23, copied from a photograph obtained by Walter (9), on a rapidly moving plate, shows how a laboratory spark spasmodically (doubtless at the period of electrical oscillation) ionizes the air from either pole and thus progressively extends and finally closes the conducting path of complete discharge. There appears also to be good evidence that the lightning discharge often builds itself up in a manner generally similar, though, perhaps, radically different, in certain details. As already implied, ordinary laboratory apparatus has a free period of electrical oscillation, and therefore an electrical discharge from such apparatus is oscillatory in nature, but as yet there seems to be no certain evidence that lightning discharges ever are distinctly oscillatory. They frequently are pulsatory, discharge after discharge taking place in the same direction and along the same path, as we shall see later; but this is an entirely different thing from being oscillatory, or consisting of a decreasing series the units of which are alternately in opposite directions.

It will be convenient, in further discussing the facts known about lightning, to classify it according to its general appearance.

Streak lightning.—When the storm is close by, the lightning discharge almost invariably appears to the unaided eye as one or more sinuous lines or streaks of vivid white or pink. Sinuous, because electrically the atmosphere is heterogeneous or unequally ionized. There often appears to be a main trunk with a number of branches, all occurring at the same time and instantaneously. At other times there seem to be two or more simultaneous but locally disconnected streaks. Frequently the discharge continues flickeringly (on rare occasions even steady, like a white-hot wire) during a perceptible time—occasionally a full second.

But all these phenomena are best studied by means of the camera, and have been so studied by several persons, among whom Walter, of Hamburg, and Larsen, of Chicago, are two of the most persistent and successful. Stationary cameras, revolving cameras, stereoscopic cameras, cameras with revolving plates, and cameras with spectrographic attachments have all been used, separately and jointly, and the results have abundantly justified the time and the labor devoted to the work.

Figure 24, copied by permission from one of Walter's unpublished negatives, shows the ordinary tracery of a lightning discharge when photographed with a stationary camera. It is only a permanent record of the appearance of the lighning to the unaided eye. Figure 25, however, also copied by Walter's kind permission from one of his unpublished photographs, is a record of the same discharge obtained with a rotating camera. It will be noted that the more nearly vertical discharge occurred but once or was single; that this discharge was quickly followed by a second along the same path to about one-fourth of the way to the earth where it branched off on a new course; that the second discharge was followed in turn at short but irregular intervals by a whole series of sequent discharges; that most of the discharges appeared as narrow intensely luminous streaks, and that one of the sequent discharges appeared, not to the eye, but on the plate of the rotating camera, as a broad band or ribbon. On close inspection it will be obvious that the plaidlike ribbon effect is due, the warp to irregularities in the more or less continuous discharge, and the woof to roughly end-on and therefore brighter portions of the streak. Another point particularly worthy of attention is the fact that while the first discharge has several side branches the following ones remain entire from end to end and are nowhere subdivided.

Figure 26, taken from a photograph obtained by Mr. Larsen, of Chicago, and kindly loaned for use here by the Smithsonian Institution, shows another series of sequent discharges similar to those of figure 25, except that in this case there was no ribbon discharge. The time of the whole discharge, as calculated by Mr. Larsen, was 0.315 second. Here, too, side branches occur with the first but only the first discharge. This, however, is not an invariable rule for occasionally, as illustrated by figure 27, copied from a published photograph by Walter, the side branches persist through two or three of the first successive discharges, but not through all. In such case each tributary when repeated follows, as does the main stream, its own original channel.

The phenomenon of sequent discharges, all along the same path, and the disappearance of the side branches with or quickly after the first discharge both seem reasonably clear. The first discharge, however produced, obviously takes place against very great resistance, and therefore under conditions the most favorable for the occurrence of side branches or ramifications. But the discharge itself leaves the air along its path temporarily highly ionized—puts a temporary line conductor with here and there a poorer conducting branch, in the atmosphere. This conductor is not only temporary (half the ions are reunited in about 0.15 second, the air being dusty) but also so extremely fragile as to be liable to rupture by the atmospheric violence it itself creates. Because partly, perhaps, of just such interruptions, and because also of the volume distribution of the electricity which prevents a sudden and complete discharge, the actual discharge is divided into a number of partials that occur sequently. Obviously, the breaks in the conducting (ionized) path, if they exist, are only here and there and but little more than sufficient to interrupt the flow. Hence the next discharge, if it occurs quickly, must follow the conducting and, therefore, original discharge path. Besides, in the

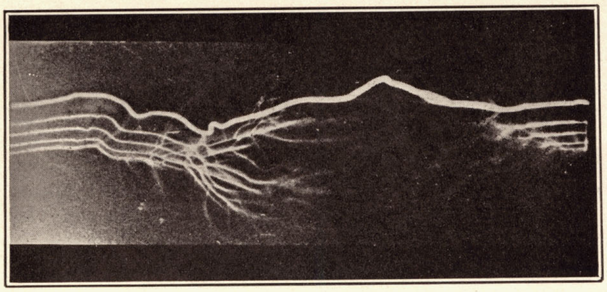

FIG. 23.—The growth of an electric spark discharge (Walter).

FIG. 24.—Streak lightning, stationary camera; companion to Fig. 25 (Walter).

FIG. 25.—Streak lightning (sequent discharges), rotating camera; companion to Fig. 24 (Walter).

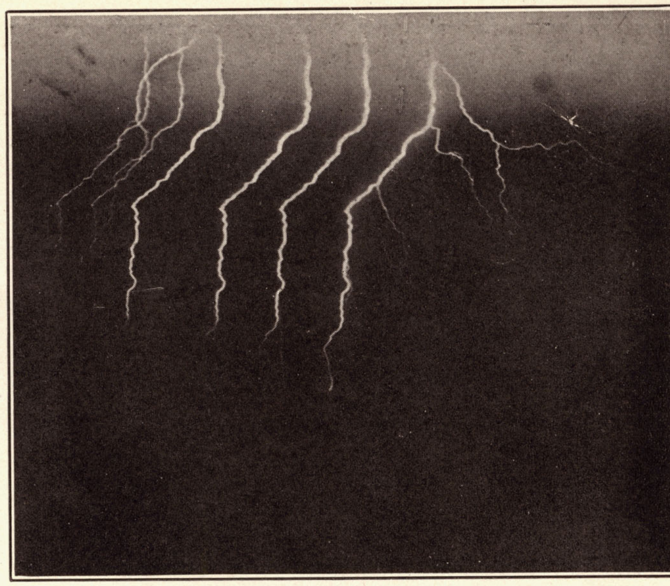

FIG. 26.—Streak lightning (sequent discharges), rotating camera (Larsen).

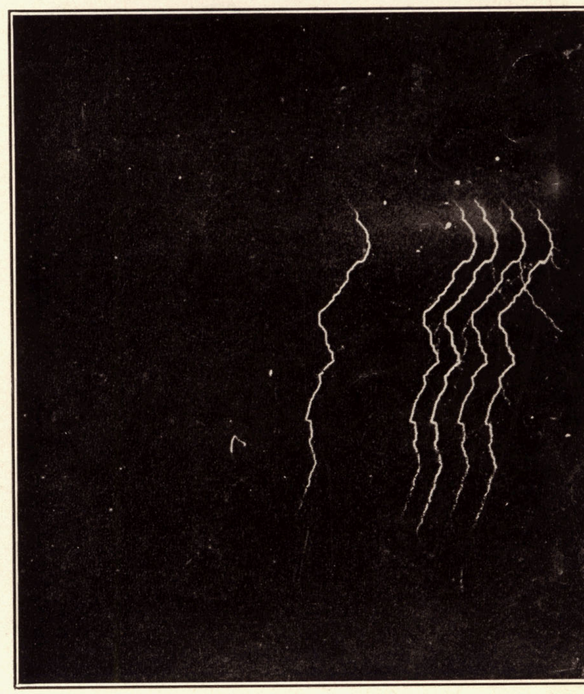

FIG. 27.—Streak lightning (sequent discharges), rotating camera (Walter).

Lightning.

Air.

λ

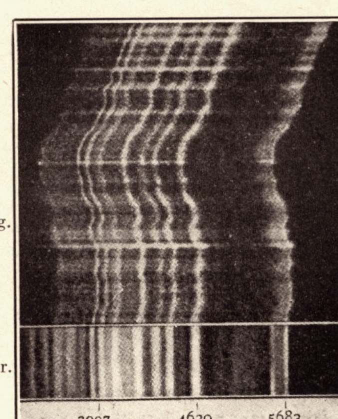

FIG. 28.—Spectrum of lightning (Fox).

subsequent discharges the original side branches will be quickly abandoned because of their greater resistance, or, what comes to the same thing, because of the more abundant ionization and consequent higher conductivity of the path of heaviest discharge.

This leaves the genesis of the initial discharge, often if not usually the only one, to be explained, and indeed this probably is, at present, the least understood of all the many thunderstorm phenomena. Judging from the voltages required to produce laboratory sparks, roughly 30,000 volts per centimeter, it is not obvious how such tremendous voltage differences can be established between clouds or between a cloud and the earth as would seem to be necessary to produce a discharge kilometers in length, as often occurs. Of course the potential of individual drops may grow in either of two ways: *a*. By coalescence of equally charged smaller drops into larger ones. In this case, since capacity is directly proportioned to the radius, the potentials of the individual drops must be proportional to the squares of their radii. *b*. By evaporation of equally charged drops. Here the potentials of the individual drops obviously is inversely proportional to their radii. In each case the tendency of the separate drops to discharge is increased, but the potential of the cloud as a whole remains unchanged. At present, therefore, one can do but little more than speculate on the subject of the primary lightning discharge, but even that much may be worth while since it helps one to remember the facts.

As already explained the electrical separation within a thunderstorm cloud is such as to place a heavily charged positive layer (lower portion of the cloud) between the earth and a much higher, also heavily charged, negative layer (upper portion of the cloud). Hence the discharges, or lightning, from the intermediate or positively charged layer may be either to the negative portion above, in some cases even to an entirely different cloud, or to the earth below. Further, through the sustaining influence and turbulence of the uprushing air there must be formed at times and places practically continuous sheets and streams of water, of course heavily charged and at high potential, and also layers and streaks of highly ionized air; that is, electrically speaking, heavily charged conducting sheets and rods, whether of coalesced drops or of ionized air, are over and over, so long as the storm lasts, momentarily placed here and there within the positively charged mass of the storm cloud.

Let us see, then, what might be expected as the result of this peculiar disposition of charges and conductors, the result, namely, of the existence of a heavily surface-charged vertical conductor in a strongly volume-charged horizontal layer or region above and below which there are steep potential gradients to negatively charged parallel surfaces.

The conductor will be at the same potential throughout, and therefore the maxima of potential gradients normal to it will be at its ends, where, if these gradients are steep enough, and the longer the conductor the steeper the gradients, brush discharges will take place. Assume, then, that a brush discharge does take place and that there is a supply of electricity flowing into the conductor to make good the loss. The brush and the line of its most vigorous ionization necessarily will be directed along the potential gradient or toward the surface of opposite charge. But this very ionization automatically increases the length of the conductor, for a path of highly ionized air is a conductor, and as the length of the conductor grows so, too, does the steepness of the potential gradient at its forward or terminal end, and as the steepness of this gradient increases the more vigorous the discharge, always assuming an abundant electrical supply. Hence, an electric spark once started within a thunderstorm cloud has a good chance, by making its own conductor as it goes, of geometrically growing into a lightning flash of large dimensions. Of course when the electrical supply is small the lightning is feeble and soon dissipated.

Whether the discharge actually does burrow its way through the atmosphere in some such manner as that indicated probably would be difficult, though not necessarily impossible, of observation. Indeed, a roughly analogous phenomenon (**10**) can be produced on a photographic plate by bringing in contact with the film, some distance apart, two conducting points attached to the opposite poles of an influence machine. Brush discharges develop about each point, but the glow at the negative pole detaches itself and slowly meanders across the plate toward the positive point. As it goes it continually builds for itself, out of the silver of the emulsion, a conducting path.

Rocket lightning.—Many persons have observed what at least seemed to be a progressive growth in the length of a streak of lightning. In some cases (**11**) this growth or progression has appeared so slow as actually to suggest the flight of a rocket, hence the name.

At first one might well feel disposed to regard the phenomenon in question as illusory, but it has been too definitely described and too frequently observed to justify such summary dismissal. Naturally, in the course of thousands of lightning discharges, many degrees of ionization, availability of electrical charge, and slopes of potential gradient are encountered. Ordinarily the growth of the discharge, doubtless, is in a geometric ratio and the progress of its end exceedingly swift, but it seems possible for the conditions to be such that the discharge can barely more than sustain itself, in which case the movement of the flash terminal may, possibly, be relatively slow.

Ball lightning.—Curious luminous balls or masses, of which C. De Jans (**12**) probably has given the fullest account, have time and again been reported among the phenomena observed during a thunderstorm. Most of them appear to last only a second or two and to have been seen at close range, some even passing through a house, but they have also appeared to fall, as would a stone (**13**), or like a meteor, from the storm cloud, and along the approximate path of both previous and subsequent lightning flashes. Others appear to start from a cloud and then quickly return, and so on through an endless variety of places and conditions.

Doubtless many reported cases of ball lightning are entirely spurious, being either fixed or wandering brush discharges or else nothing other than optical illusions, due in most cases probably to persistence of vision. But here, too, as in the case of rocket lightning, the amount and excellence of observational evidence forbid the assumption that all such phenomena are merely subjective. Possibly in some instances, especially those in which it is seen to fall from the clouds, ball lightning may be only extreme cases of rocket lightning, cases in which the discharge for a time just sustains itself. A closely similar idea has been developed in detail by Toepler (**14**). It may either disappear wholly and noiselessly, as often reported, or it could perhaps suddenly gain in strength and instantly disappear, as sometimes observed, with a sharp abrupt clap of thunder.

To say that all genuine cases of ball lightning, those that are not mere optical illusions are stalled thunderbolts, certainly may sound very strange. But that indeed is just what they are according to the above speculation, a speculation that recognizes no difference in kind between streak, rocket, and ball lightning, only differences in the amounts of ionization, quantities of available electricity and steepness of potential gradients.

Sheet lightning.—When a distant thundercloud is observed at night one is quite certain to see in it beautiful illuminations, looking like great sheets of flame, that often flicker and glow in exactly the same manner as does streak lightning for well-nigh a whole second. In the daytime and in full sunlight the phenomenon when seen at all appears like a sudden sheen that travels and spreads here and there over the surface of the cloud. Certainly in most cases, so far as definitely known in all cases this is only reflection from the body of the cloud of streak lightning in other and invisible portions. Conceivably a brush or coronal discharge may take place from the upper surface of a thunderstorm cloud, but one would expect this to be either a faint continuous glow or else a momentary flash coincident with a discharge from the lower portion of the cloud to earth or to some other cloud. But, as already stated, only reflection is definitely known to be the cause of sheet lightning. Coronal effects seem occasionally possible, but that they are ever the cause of the phenomenon in question has never clearly been established and appears very doubtful. It has often been asserted, too, that there is a radical difference between the spectra of streak and sheet lightning, but even this does not appear ever to have been photographically proved.

Beaded lightning.—Discontinuous or beaded streaks of lightning have been reported from time to time. Indeed the author himself has several times seen, or had the impression of seeing, this phenomenon, but with one or two doubtful exceptions he felt practically certain that it was only an optical illusion. In addition to visual observations of the kind just described many photographs showing streaks of light broken into more or less evenly spaced dashes have been obtained and reported as photographs of beaded lightning. Without exception, however, these seem certainly to be nothing other than the photographs of alternating current electric lights, taken with the camera in motion. The objective reality, therefore, of beaded lightning does not seem at all well established, at least not sufficiently well to justify any serious effort to explain it.

Return lightning.—This is commonly referred to as the return shock, and is only those relatively small electrical discharges that take place here and there from objects on the surface of the earth coincidently with lightning flashes, and as a result of the suddenly changed electrical strain. These discharges are always small in comparison with the main lightning flash, but at times they are sufficient to induce explosions, to start fires, and even to take life.

Dark lightning.—When a photographic plate is exposed to a succession of lightning flashes, it occasionally happens that one or more of the streak images, on development, exhibits the "Clayden effect"—that is, appears completely reversed—while the others show no such tendency. Obviously, then, on prints from such a negative the reversed streaks must appear as dark lines, and for that reason the lightning flashes that produced them have been called "dark lightning." There is, of course, no such thing as dark lightning, but the photographic phenomenon that gave rise to the name is real, interesting, and reproducible at will in the laboratory (**15**).

Temperature.—What the temperature along the path of a lightning discharge is no one knows, but it obviously is high, since it frequently sets fire to buildings, trees, and many other objects struck. In an ordinary electrical conductor the amount of heat generated in a given time by an electric current is proportional to the product C^2RT, in which C is the strength of the current, R the ohmic resistance, and T the time in question during which C and R are supposed to remain constant. In a spark discharge of the nature of lightning some of the energy produces effects, such as decomposition and ionization, other than mere local heating, but as experiment shows, a great deal of heat is generated, according, so far as we know, to the same laws that obtain for ordinary conductors. Hence extra heavy discharges, like extra large currents, produce excessive heating, and therefore are far more liable than are light ones to set on fire any objects that they may hit.

Visibility.—Just how a lightning discharge renders the atmosphere through which it passes luminous is not definitely known. It must and does make the air path very hot, as we have seen, but no one has yet succeeded, by any amount of ordinary heating, in rendering either oxygen or nitrogen luminous. Hence it seems well nigh certain that the light of lightning flashes owes its origin to something other than high temperature, probably to internal atomic disturbances induced by the swiftly moving electrons of the discharge.

Spectrum.—Lightning flashes are of two colors, white and pink or rose. The rose-colored flashes, when examined in the spectroscope, show several lines due to hydrogen which, of course, is furnished by the decomposition of some of the water along the lightning path. The white flashes, on the other hand, show no hydrogen lines or at most but faint ones. As one might suspect, the spectrum of a lightning flash and that of an ordinary electric spark in air are practically identical. This is well shown by figure 28, copied from an article on the spectrum of lightning by Fox (**16**), in which the upper or wavy portion is due to the lightning and the lower or straight portion to a laboratory spark in air.

It is often asserted that the spectrum of streak lightning consists wholly of bright lines and that sheet lightning gives only nitrogen bands; and from this it is argued that the latter is not a mere reflection of the first. This assertion is not supported by figure 27, the brightest portions of which, the portions that would the longest be seen as reflection grew steadily feebler, coincide with strong nitrogen bands. In this connection, however, it should be remembered that accurate wavelength measurements, and therefore positive identification of the lines of lighting spectra, is not possible, owing to the small dispersion or separation of the lines on all such negatives so far reported.

Duration.—The duration of the lightning discharge is exceedingly variable, ranging from 0.0002 second for a single flash to, in rare cases, even a full second or more for a multiple flash consisting of a primary and a series of sequent flashes. On rare occasions a dischare of long duration appears *to the eye* to be steady like a glowing solid. Possibly the best measurements of the shorter intervals were made by De Blois (**17**) with the aid of a high-frequency oscillograph. He found the durations of 38 single peaks, averaging 0.00065 second, to range from 0.0002 second to 0.0016 second. Flashes that last as long as a few tenths or even a few hundredths of a second are almost certainly multiple, consisting of a succession of apparently individual discharges occurring at unequal intervals. Occasionally a practically continuous discharge of varying intensity, but all the time strong enough to produce luminosity, will last a few hundredths of a second.

It must be remembered that the duration of even a single discharge and the length of time to complete the circuit, or ionize a path, from cloud to earth, say, are entirely different things. The latter seems usually (rocket and ball lightning may furnish exceptions) to be of exceedingly short duration, while the former depends upon the supply of electricity and the ohmic resistance directly and upon the potential difference inversely.

Discharges direct, not alternating.—Years ago some one for some reason or other, or for no reason, made the statement that the lightning flash is alternating and of high frequency, like the discharge of a Leyden jar, and forthwith, despite the fact that all evidence is to the contrary, it became a favorite dogma of the textbook, passed on unquestioned from author to author and handed down inviolate from edition to edition. There often are a number of successive discharges in a fraction of a second, as photographs taken with a revolving camera show, but they are not only along the same path but also in the same direction. This is obvious from the fact that when the side branches persist, as in figure 26, through two or more partial or sequent discharges, they are always turned in the same direction. It is also proved by the direct evidence of the oscillograph (18).

In the case of each separate discharge also the direction seems constant. It may vary in strength, or pulsate, but, apparently, it does not alternate. There are several reasons for concluding that lightning discharges are direct and not alternating, of which the following cover a wide range and probably are the best:

a. Lightning operates telegraph instruments. If the discharge were alternating it would not do so.

b. At times it reverses the polarity of dynamos. This requires a direct and not a high-frequency alternating discharge.

c. The oscillograph (19) shows each surge or pulsation, as well as the whole flash, to be unidirectional.

d. The relative values of the ohmic resistance, the self-induction, and the capacity, in the case of a lightning discharge, appear usually, if not always, to be such as to forbid the possibility of oscillations.

It has been shown that whenever the product of the capacity by the square of the resistance is greater than four times the self-induction, or, in symbols, that whenever

$$CR^2 > 4L$$

oscillations are impossible. Undoubtedly all these terms vary greatly in the case of lightning discharges, but R, presumably, is always sufficiently large to maintain the above inequality and therefore absolutely to prevent oscillations.

Possibly a calculation giving roughly the numerical order of the terms involved would be helpful. For this purpose assume a cloud whose undersurface is circular with a radius of 3 kilometers, and whose height above the ground is 1 kilometer, and let there be a discharge from the center of the cloud base straight to the earth: Find a probable value for the self-induction and capacity, and from these the limiting value of the resistance to prevent oscillations, or the value of R in the equation

$$CR^2 = 4L.$$

To find L we have the fact that the coefficient of self-induction is numerically equal to twice the energy in the magnetic field per unit current in the circuit, and the further fact that per unit volume this energy is numerically equal to $H/8\pi$, in which H is the magnetic force. Let a be the radius of the lightning path and assume the current density in it to be uniform. Let b be the equivalent radius of the cylinder, concentric with the lightning path, along which the return or displacement current flows. In this case the energy W of the magnetic field per centimeter length of the discharge is given by the equation

$$W = \log_e \frac{b}{a} + \tfrac{1}{2}.$$

Let $b=2$ kilometers and $a=5$ centimeters. Then $W = \log_e 4\times10^4 + \frac{1}{2} = 11$, approximately. Hence the energy of the magnetic field per unit current for the whole length, 1 kilometer, of the flash is represented by the equation

$$W10^5 = 11\times10^5,$$

hence the self-induction $= 22\times10^5 = 22\times10^{-4}$ henry.

To find C we shall assume a uniform field between the cloud and the earth. As a matter of fact this field is not uniform, and the calculated value of C, based upon the above assumption, is somewhat less than its actual value. Assuming, then, a uniform field we have

$$C = \frac{a}{4\pi d} = \frac{\pi 9\times10^{10}}{4\pi\times10^5} = 225\times10^3 = 25\times10^{-8} \text{ farad, about.}$$

Hence, substituting in the equation

$$CR^2 = 4L,$$

we get

$$R = 190 \text{ ohms per kilometer, approximately.}$$

Neither a, the radius of the lightning path, nor b, the equivalent radius of the return current is accurately known, but from the obviously large amount of suddenly expanded air necessary to produce the atmospheric disturbances incident to thunder it would seem that 1 centimeter would be the minimum value for a. Also, from the size of thunder clouds, it appears that 10 kilometers would be the maximum value for b.

On substituting these extreme values in the above equations, we get

$$R = 200 \text{ ohms per kilometer, roughly.}$$

From the fact that C varies inversely and L directly as the altitude of the cloud it follows that, other things remaining equal, the height of the cloud has no effect on the value of R per unit length.

If the altitude is kept constant and the size of the cloud varied C will increase directly as the area, and L will increase directly as the natural logarithm of the equivalent radius of the cylinder of return current. Assuming the area of the cloud base to be 1 square kilometer, which certainly is far less than the ordinary size, and computing as above we find

$$R = 850 \text{ ohms per kilometer, roughly.}$$

Again, assuming the base area to be 1,000 square kilometers, an area far in excess of that of the base of an ordinary thunderstorm cloud, we find

$$R = 35 \text{ ohms per kilometer, roughly.}$$

It would seem, therefore, that a resistance along the lightning path of the order of 200 ohms per kilometer, or 0.002 ohm per centimeter, would suffice, in most cases, absolutely to prevent electrical oscillations between cloud and earth. In reality the total resistance includes, in addition to that upon which the above calculations are based, the resistance in parallel of the numerous feeders or branches within the cloud itself. In other words, the assumption that the resistance of the condenser plates is negligible may not be strictly true in the case of a cloud. Nor is this the only uncertainty, for no one knows what the resistance along the path of even the main discharge actually is; though, judging from the resistance of an oscillatory electric spark (**20**), it, presumably, is much greater than the calculated limiting value; and if so, then lightning flashes, as we have seen, must be unidirectional and not alternating.

Length of streak.—The total length of a streak of lightning varies greatly. Indeed the brush discharge so gradually merges into the spark and the spark into an unmistakable thunderbolt that it is not possible sharply to distinguish between them, nor, therefore, to set a minimum limit to the length of a lightning path. When the discharge is from cloud to earth the length of the path is seldom more than 2 to 3 kilometers, but, in the case of low-lying clouds, may be much less, and especially so when they envelop a mountain peak.

On the other hand, when the discharge is from cloud to cloud the path generally is far more tortuous and its total length much greater, amounting at times to 10, 15, and even 20 kilometers.

Discharge, where to where?—As already explained, lightning discharges may be from cloud to earth, from one part to another of the same cloud, or from cloud to cloud. But since the great amount of electrical separation, without which the lightning could not occur, takes place within the rain cloud, it follows that this is also likely to be the seat of the steepest potential gradients. Hence it would appear that lightning must occur most frequently between the lower and the upper portions of the same cloud, and this is fully supported by observations. The next in frequency, especially in mountainous regions, is the discharge from cloud (lower portion) to earth, and the least frequent of all, ordinarily, those that take place between one and another entirely independent or disconnected clouds.

Explosives effects.—The excessive and abrupt heating caused by the lightning current explosively and greatly expands the column of air through which it passes. It even explosively vaporizes such volatile objects as it may hit that have not sufficient conductivity to carry it off. Hence, chimneys are shattered, shingles torn off, trees stripped of their bark or utterly slivered and demolished, kite and other wire fused or volatilized, holes melted through steeple bells and other large pieces of metal, and a thousand other seeming freaks and vagaries wrought.

Many of the effects of lightning appear at first difficult to explain, but, except the physiological and, probably, some of the chemical, all depend upon the sudden and intense heating along its path.

Chemical effects.—As is well known, oxides of nitrogen and even what might be termed the oxide of oxygen, or ozone, are produced along the path of an electric spark in the laboratory. Therefore one might expect an abundant formation, during a thunderstorm, of these same compounds. And this is exactly what does occur, as observation abundantly shows. It seems probable, too, that some ammonia must also be formed in this way, the hydrogen being supplied by the decomposition of raindrops and water vapor.

In the presence of water or water vapor these several compounds undergo important changes or combinations. The nitrogen peroxide (most stable of the oxides of nitrogen) combines with water to produce both nitric and nitrous acids; the ozone with water gives hydrogen peroxide and sets free oxygen; and the ammonia in the main merely dissolves, but probably also to some extent forms caustic ammonia and hydrogen. Symbolically the reactions seem to be as follows:

$$2NO_2 + H_2O = HNO_3 + HNO_2.$$
$$O_3 + H_2O = H_2O_2 + O_2.$$
$$2NH_3 + 2H_2O = 2NH_3OH + H_2.$$

The ammonia and also both the acids through the production of soluble salts are valuable fertilizers. Hence, wherever the thunderstorm is frequent and severe, especially, therefore, within the tropics, the chemical actions of the lightning may materially add, as has recently been shown (**21**), to the fertility of the soil and the growth of crops.

Danger.—It is impossible to say much of value about the danger from lightning. Generally it is safer to be indoors than out during a thunderstorm, especially if the house has a well-grounded metallic roof. If outdoors it is far better to be in a valley than on the ridge of a hill, and it is always dangerous to take shelter under a tree—the taller the tree, other things being equal, the greater the danger. Some varieties of trees appear to be more frequently struck, in proportion to their numbers and exposure, than others, but no tree is immune. It seems that, in general, the trees most likely to be struck are those that have either an extensive root system, like the locust, or deep tap roots, like the pine, and this for the very obvious reason that they are the best grounded and therefore offer, on the whole, the least electrical resistance.

Finally, if one has to be outdoors and exposed to the danger of a violent thunderstorm it is advisable, so far as danger from the lightning is concerned, to get soaking wet, because wet clothes are much better conductors, and dry ones poorer, than the human body. In extreme cases it might even be advisable to lie flat on the wet ground.

As just implied, the contour of the land is an important factor in determining the relative danger from lightning because, obviously, the chance of a cloud-to-earth discharge, the only kind that is dangerous, varies inversely as the distance between them. Hence thunderstorms are more dangerous in mountainous regions, at least in the higher portions, than over a level country. For this same reason also, distance of cloud to earth, there exists on high peaks a level or belt of maximum danger, the level, approximately of the base of the average cumulus cloud. The tops of the highest peaks are seldom struck, simply because the storm generally forms and runs its course at a lower level.

Clearly, too, for any given section the lower the cloud the greater the danger. Hence a high degree of humidity is favorable to a dangerous storm, partly because the clouds will form at a low level and partly because the precipitation will be abundant. Hence, too, a winter thunderstorm, because of its generally lower clouds, is likely to be more dangerous than an equally heavy summer one.

The ceraunograph.—Various instruments, based upon the principles of "wireless" receivers, have been devised for recording the occurrence of lightning discharges. Of course the sensitiveness of the instrument, the distance and the magnitude of the discharge all are factors that affect the record, but by keeping the sensitiveness constant, or nearly so, it is possible with an instrument of this kind to estimate the approximate distance, progress, and to some extent even the direction of the storm. Nevertheless there does not appear to be much demand for this information, and therefore at present the ceraunograph is but sparingly used.

Thunder.—For a long while no one had even a remotely satisfactory idea in regard to the cause of thunder, and it is not a rare thing even yet to hear such a childish explanation as that it is the noise caused by the bumping or rubbing of one cloud against another.

As above explained, because of the sudden and intense heating due to the lightning discharge the air column through which it passes is so greatly and so abruptly expanded as to simulate in every detail a violent explosion, and therefore to send out from every portion of its path a steep compression wave, which, of course, is the real physical cause of the thunder. The expansion, obviously, is followed by a cooling and contraction, but though this action is rapid it probably is not nearly rapid enough to have anything to do with the production of thunder, though many have suggested it as the whole cause.

Rumbling.—Probably the most distinctive characteristic of thunder is its long-continued rumbling and great variation in intensity. Several factors contribute to this peculiarity, among them:

Inequalities in the distances from the observer to the various portions of the lightning's path. Hence the sound, which ordinarily travels about 330 meters per second in the air, will not all reach him at the same time, but continuously over an appreciable interval of time.

Crookedness of path. Because of this condition it often happens that sections of the path here and there are, each through its length, at nearly the same distance from the observer or follow roughly the circumferences of circles of which he is the center, while other portions are directed more or less radially from him. This would account for, and doubtless in a measure is the correct explanation of, some of the loud booming effects or crashes that accompany thunder.

Succession of discharges. When, as often happens, several discharges follow each other in rapid succession there is every opportunity for all sorts of irregular mutual interference and reinforcement of the compression waves or sound impulses they send out.

Reflection. Under favorable conditions the echo of thunder from clouds, hills, and other reflecting objects certainly is effective in accentuating and prolonging the noise and rumble. But the importance of this factor generally is greatly overestimated, for ordinarily the rumble is substantially the same whether over the ocean, on the prairies, or among the mountains.

Distance heard.—The distance to which thunder can be heard seldom exceeds 25 kilometers, while ordinarily, perhaps, it is not heard more than half so far. To most persons, familiar with the great distances to which the firing of large cannon is still perceptible, the relatively small distances to which thunder is audible is quite a surprise. It should be remembered, however, that both the origin of the sound and often the air itself as a sound conductor are radically different in the two cases. The firing of cannon or any other surface disturbance is heard farthest when the air is still and when, through temperature inversion or otherwise, it is so stratified as in a measure to conserve the sound energy between horizontal planes. Conversely, sound is heard to the least distance when the atmosphere is irregular in respect to either its temperature or moisture distribution, or both, for these conditions favor the production of internal sound reflections and the dissipation of energy. Now the former or favorable conditions occasionally obtain during the production of ordinary noises, including the firing of cannon, but never obtain during a thunderstorm. In fact, the thunderstorm is especially likely itself to establish the second set of the above conditions, or those least favorable to the far carrying of sound.

Then, too, when a cannon, say, is fired the noise all starts from the same place, the energy is concentrated, while in the case of thunder it is stretched out over the entire length of the lightning path. In the first case the energy is confined to a single shell; in the second it is diffused through an extensive volume. It is these differences in the concentration and the conservation of the energy that cause the cannon to be heard much farther than the heaviest thunder, even though the latter almost certainly produces much the greater total atmospheric disturbance.

Normal atmospheric electricity.—The only reason for mentioning normal atmospheric electricity in connection with thunderstorms is to emphasize the fact that, contrary to what many suppose to be the case, there is but little relation, in the sense of cause and effect, between these two phenomena. Thus while the difference in electrical potential between the surface of the earth and a point at constant elevation is roughly the same at all parts of the world, the number and intensity of thunderstorms vary greatly from place to place. Further, while the potential gradient at any given place is greatest in winter the number of thunderstorms is most frequent in summer, and while the gradient, in the lower layer of the atmosphere, at many places, usually is greatest from 8 to 10 o'clock, both morning and evening, and least at 2 to 3 o'clock p. m. and 3 to 4 o'clock a. m., no closely analogous relations hold for the thunderstorm.

Probably the most interesting conclusion in regard to normal atmospheric electricity so far drawn from observation and experiment is this: That the earth everywhere, land and water and from pole to pole, is a negatively charged sphere of practically constant surface density, surrounded by an atmosphere so conducting that it is constantly carrying away a current that amounts on the whole to about 1,000 amperes.

Where the supply of negative electricity comes from that keeps the surface of the earth on the whole negatively charged in spite of this steady great loss, or how the outgoing current is compensated, no one knows. Rain does not help matters for, as we have seen, that is prevailingly positive, whereas we need, to compensate the loss, to bring back negative electricity and a great deal of it. Neither, so far as known, is compensation supplied by means of the lightning, for, in the great majority of cases, this, too, is positive from cloud to earth. And so the puzzle remains. As Simpson (22) puts it:

> A flow of negative electricity takes place from the surface of the whole globe into the atmosphere above it, and this necessitates a return current of more than 1,000 amperes; yet not the slightest indication of any such current has so far been found, and no satisfactory explanation for its absence has been given.

Much more, of course, might be said on this subject, for it is a big one on which many have labored, but perhaps the above is sufficient for the purpose of this final section, namely, to show that, contrary to opinions often held, there is no obvious and close relation between the thunderstorm and normal atmospheric electricity; that, according to our best evidence, they are distinct and independent phenomena.

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